

**RISK MANAGEMENT OF GROUNDWATER POLLUTION  
- A KNOWLEDGE-BASED APPROACH**

**BY**

**BRIDGET BUTLER**

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## ABSTRACT

Risk assessment and risk management now underpin environmental protection in the UK. Risk assessment provides for a structured and systematic analysis of a problem, and is an objective tool to inform risk management decisions. In particular, risk assessment can assist in the prioritisation of management activities to direct resources more effectively to significant risks. However, the application of risk assessment remains *ad hoc* and often focused on quantified approaches. The problem of how to integrate the results of a risk assessment into decision-making processes remains. The objective of this research was to assess whether a knowledge-based approach could be usefully applied to risk management decisions associated with the protection of groundwater. The use of a knowledge-based system offers considerable potential to support regulatory decision-making relating to environmental risks. Such systems utilise expert knowledge to solve specific problems as an expert would but without requiring specialist or skilled users. This research describes the development of a prototype decision-support system to assist non-specialist regulatory personnel, in the prioritisation of risks and management activities relating to groundwater threats from hydrocarbon point-sources. The research focused on the knowledge acquisition process using semi-structured interviews, concept sorting and risk rating to identify the type of information required by the expert in their decision-making processes and also to distinguish any differences of approach between experts and 'non-experts'. A conceptual model was developed that represented expert decision-making and problem solving. This model was used to develop the prototype decision-support system which was subsequently evaluated by experts and users, resulting in system refinements. A positive response to the usability and utility of the system was received from both expert and user groups, suggesting a knowledge-based approach can be usefully applied to risk management decisions associated with the protection of groundwater.

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## ABBREVIATIONS USED

### Countries

UK	United Kingdom
USA	United States of America

### Organisations

ANZECC	Australian and New Zealand Environment and Conservation Council
API	American Petroleum Institute
ASTM	American Society for the Testing of Materials
BGS	British Geological Survey
BSI	British Standards Institution
CCME	Council of Canadian Ministers of the Environment
CIRIA	Construction Industry Research and Information Association (UK)
DETR	Department of the Environment, Transport and the Regions (UK)
DOE	Department of the Environment (UK)
EA	Environment Agency for England and Wales
EEA	European Environment Agency
HMIP	Her Majesty's Inspectorate of Pollution (England and Wales)
HSE	Health and Safety Executive (UK)
ICRCL	Interdepartmental Committee for the Redevelopment of Contaminated Land (UK)
IOP	Institute of Petroleum (UK)
MAFF	Ministry of Agriculture, Fisheries and Food (UK)
MOD	Ministry of Defence (UK)
NRA	National Rivers Authority (England and Wales)
OECD	Organisation for Economic Co-operation and Development
OSWER	Office of Solid Waste and Emergency Response (USEPA)
OUST	Office for Underground Storage Tanks (USEPA)
PIRI	Partnership in RBCA Implementation (USEPA)
RCEP	Royal Commission on Environmental Pollution (UK)
SEPA	Scottish Environmental Protection Agency
UKPIA	United Kingdom Petroleum Industry Association
UN	United Nations
USEPA	United States Environmental Protection Agency
WRA's	Waste Regulation Authorities (England and Wales)

### Terms

AERAM	Air Emissions Risk Assessment Model
AERIS	Aid for Evaluating the Redevelopment of Industrial Sites
ATG	Automatic Tank Gauging
DNAPL	Dense Non-Aqueous Phase Liquid
DSS	American Petroleum Institute Decision Support System
EIA	Environmental Impact Assessment
ESTA	Expert System for Text Animation (Prolog Development Center)
EXPRES	Expert System for Pesticide Regulatory valuations and Simulations
FRP	Fibreglass Reinforced Plastic
GIS	Geographical Information System
GRP	Glass Reinforced Plastic
HALO	Hazard Assessment of Landfill Operations
HARRIS	Hydrocarbon And Risk-Related Information System
HESP	Human Exposure to Soil Pollutants
HRS	Hazard Ranking System
IPC	Integrated Pollution Control
LEAP	Local Environmental Action Plan
LFG	Landfill Gas
LNAPL	Light Non-Aqueous Phase Liquid
LUST	Leaking Underground Storage Tank
MEPAS	Multi-media Environmental Pollution Assessment System

MTBE	Methyl-Tertiary-Butyl-Ether
NAPL	Non-Aqueous Phase Liquid
OFPD	Over-Fill Protection Device
OPRA	Operator and Pollution Risk Appraisal
PAH	Poly Aromatic Hydrocarbon
PARI	Potential Abstraction Risk Index
PC	Personal Computer
PCE	Tetrachloroethylene
PFA	Pulverised Fuel Ash.
PPG	Planning Policy Guidance Note
QRA	Quantified Risk Assessment
RAISON™	Regional Analysis by Intelligent Systems ON microcomputers
RBCA	Risk-Based Corrective Action
RBR	Risk Based Remediation Model
SPT	Source-Pathway-Target
STP	Source-Target-Pathway
SPZ	Source Protection Zone
SSSI	Site of Special Scientific Interest
TCE	Trichloroethylene
UST	Underground Storage Tank

#### **Legislation Referred to**

Petroleum (Consolidation) Act 1928  
Petroleum (Transfer of Licences) Act 1936  
Control of Pollution Act 1974  
Health and Safety at Work Act 1974  
EC Directive (80/68/EEC) The Protection of groundwater against pollution caused by certain dangerous substances  
Control of Substances Hazardous to Health (COSHH) 1988  
Environmental Protection Act 1990  
Town and Country Planning Act 1990  
Water Resources Act 1991  
Waste Management Licensing Regulations 1994 SI No. 1056  
Environment Act 1995  
Comprehensive Environmental Response Compensation and Liability Act 1980 (CERCLA) (USA)  
Superfund Amendments and Reauthorisation Act 1986 (SARA) (USA)  
Resource, Conservation and Recovery Act 1984 (RCRA) (USA)  
Underground Storage Tanks; Technical Requirements and State Program Approval; Final Rules, 1988 - Federal Register 40 CFR Part 280 (USA)

## GLOSSARY OF TERMS

- Abstraction** - Removal of water from groundwater, usually by pumping
- Adsorption** - Process by which a thin layer of a substance accumulates on the surface of a solid substance
- Algorithm** - A formal procedure guaranteed to produce correct or optimal solutions
- Aquifer** - Permeable strata that can transmit and store water in significant quantities
- Artificial Intelligence** - The part of computer science concerned with developing intelligent computer programs
- Attenuation** - Breakdown or dilution of a contaminant in water for example
- Backward Chaining** - An inference method where the system starts with what it wants to prove e.g. Z, and tries to establish the facts it needs to prove Z.
- Baseflow** - That part of the flow in a watercourse made up of groundwater and discharges. It sustains the water course in dry weather
- Biodegradation** - Microbial breakdown of a compound
- Capillary Fringe** - The layer of rock immediately above the water table in which water is held by capillarity
- Capture Zone** - Area around a source of groundwater (e.g. abstraction point) which contributes water to the discharge
- Certainty Factor** - A number that measures the certainty or confidence one has that a fact or rule is valid
- Concept Sorting** - A technique used to identify ways an expert sees relationships between a fixed set of concepts. The expert using a set of cards on which a concept word is printed, sorts the cards into piles. This process is repeated with different piles representing different relationships between concepts
- Confined Aquifer** - Where permeable strata are covered by a substantial depth of impermeable strata such that the cover prevents infiltration
- Conservative Pollutant** - Pollutant which can move readily through the aquifer with little reaction with the rock matrix and which are unaffected by biodegradation (e.g. chloride)
- Contaminated Land** - Land that is causing or has the potential to cause significant harm or pollution of controlled waters
- Contamination** - The presence of a foreign substance which may or may not cause harm (see pollution)
- Controlled Waters** - Inland freshwaters (water courses, lakes etc.) and groundwater
- Darcy's Law** - An empirical equation which relates the flow of water in an aquifer to the area through which flow can occur, the permeability of the rock and the hydraulic gradient
- Darcian Flow** - Groundwater flow which obeys Darcy's Law e.g. intergranular flow
- Database** - The set of facts, assertions, and conclusions used to match against the rules in a rule-based system (often has a broader meaning)
- Declarative Knowledge** - Knowledge about facts and things, i.e. general facts about the world
- Diffuse Source Pollutants** - Pollution from widespread activities with no one discrete source (e.g. nitrate pollution from agricultural activities)
- Diffusion** - The process by which ions and molecules dissolved in water move from areas of higher concentration to areas of lower concentration
- Domain Knowledge** - Problem-specific knowledge about the problem domain; e.g. knowledge about geology in a knowledge system for finding mineral deposits
- Drift Deposits** - Term used to include all unconsolidated superficial deposits (e.g. fluvioglacial, alluvium etc.) overlying solid rocks
- Ecosystem** - A system involving the interactions between a community and its non-living environment
- Effective Porosity** - That part of the total porosity which can transmit water
- End-User** - The person who uses the finished knowledge system; the person for whom the system was developed (see User)
- Evapotranspiration** - Loss of water from the land surface through the transpiration of plants and evaporation from the soil
- Expert** - A person who through years of training and experience has become extremely proficient at problem solving in a particular problem area
- Expert System** - A computer program using expert knowledge to attain high levels of performance in a narrow problem area. These programs typically represent knowledge symbolically, examine and explain their reasoning processes, and address problem areas that require years of special training and education for humans to be termed an expert. (see also knowledge system)
- Explanation Facility** - The part of a knowledge system that explains how solutions were reached and justifies the steps used to reach them
- Fissure Flow** - Flow through rock via natural cracks in the rock (as opposed to Intergranular Flow)
- Forward Chaining** - An inference method where rules are matched against facts to establish new facts

- Fractures/Fissures** - Natural cracks in rocks that enhance rapid water movement
- Frame** - A knowledge representation method that associates features with nodes representing concepts or objects. The features are described in terms of attributes (called slots) and their values
- Fuzzy Logic** - An approach to approximate reasoning in which truth values and quantifiers are defined as probability distributions that carry linguistic labels, such as true, very true, not very true, many, not very many, few and several. The rules of inference are approximate, rather than exact, in order to better manipulate information that is incomplete, imprecise or unreliable
- Groundwater** - Water in the saturated zone i.e. below the water table
- Harm** - An adverse event affecting the health of living organisms or other interference with the ecological systems of which they form a part and in the case of man includes offence to any of his senses or harm to his property
- Hazard** - Property or situation that has the potential to cause harm to a defined target
- Head** - Groundwater height above a reference level
- Heuristic** - A heuristic is defined as a rule of thumb or generally proven method to obtain a result given particular information
- Hydrocarbon** - Compounds of the elements hydrogen and carbon. Includes the DNAPLs and LNAPLs
- Hydrogeological Characteristics** - Properties relating to flow of water through rocks, e.g. permeability, transmissivity, porosity etc.
- Impermeable** - Having texture that does not permit water to move through it under the head differences ordinarily found in the subsurface waters
- Inference Chain** - The sequence of steps or rule applications used by a rule-based system to reach a conclusion
- Inference Engine** - That part of a knowledge system or expert system that contains the general problem solving knowledge, i.e. not problem specific
- Inference Method** - The technique used by the inference engine to access and apply the domain knowledge, e.g. forward chaining or backward chaining
- Inorganic** - Chemicals which are not carbon-based, such as salt, nitrate fertilisers etc.
- Intergranular Flow** - Groundwater flow between individual rock grains which obeys Darcy's Law (Darcian flow)
- Interpreter** - The part of the inference engine that decides how to apply the domain knowledge
- Knowledge** - In terms of knowledge systems, the information the computer must have to behave intelligently
- Knowledge Acquisition** - The task of gathering information, generally from what ever source it is available from
- Knowledge Base** - The portion of a knowledge system or expert system that contains the problem specific knowledge
- Knowledge-Based System** - See knowledge system
- Knowledge Elicitation** - A set of techniques and methods that attempt to elicit an expert's knowledge through some form of direct interaction with that expert - a sub-task of knowledge acquisition
- Knowledge Engineer** - The person who designs and builds the knowledge system
- Knowledge Engineering** - The process of building knowledge systems
- Knowledge Representation** - The process of structuring knowledge about a problem in a way that makes the problem easier to solve
- Knowledge System** - A program in which the problem-specific knowledge is explicit and separate from the programs other knowledge
- Laddered grids** - The expert and the knowledge engineer construct a graphical representation of the domain in terms of the relations between domain or problem solving elements to produce a two-dimensional graph where nodes are connected by labelled arcs
- Leaching** - Removal of soluble substances by action of water percolating through soil, waste or rock
- Off-the-job Protocol Analysis** - The expert comments retrospectively on a problem solving session, by video recording for example
- On-the-job Protocol Analysis** - The expert is recorded solving a problem and concurrently a commentary is made. There are two kinds, Self-Report where the expert solving the problem describes what they are doing and Shadowing where another expert is describing what is going on
- Organic** - Chemicals which are carbon-based such as pesticides, dry cleaning solvents etc.
- Outcrop** - Where strata are at the surface, even though they may be covered by soil cover
- Pathway** - A link between a potential or actual source of pollution and an identified target i.e. Source-Pathway-Target model
- Permeability** - Measure of a soil or rock's capacity to transmit water

- Petroleum** - A mixture of hydrocarbons e.g. petrol (also used outside the UK as 'petroleum fuels' which includes diesel, petrol etc.)
- pH** - The degree of acidity (or alkalinity) of a solution or soil expressed in terms of the pH scale
- Porosity** - Ratio of the void space to the total volume of the rock
- Pollution** - The introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological systems damage to structures or amenity, or interference with legitimate uses of the environment
- Procedural knowledge** - Knowledge of how to perform various cognitive activities i.e. what actions to take under what conditions (see Declarative knowledge)
- Protection Zone** - An area of land which the water regulatory authority has determined should be delineated around a source or over a catchment in order to provide a degree of protection against a range of activities
- Protocol Analysis** - A generic term for a number of different ways of performing some form of analysis of the expert(s) actually solving problems in the domain (see on-the-job and off-the-job analysis)
- Prototype** - The system solves a portion of the problem undertaken, suggesting that the approach is viable and system development is achievable. The system displays credible performance on the entire problem but may be fragile due to incomplete testing and revision
- Receptor** - See Target
- Recharge** - Water which percolates downwards from the surface into groundwater
- Representation** - The process of formulating or viewing a problem so it will be easier to solve
- Risk** - The probability that a particular event adverse event occurs during a stated period of time: i.e. the probability of harm (often defined especially in the US, as a function of exposure and toxicity)
- Risk Ranking** - The process of assigning scores to risk-related terms and then ordering them in terms of that score, so each ranking can appear only once
- Risk Rating** - The process of assigning scores to a set of risk-related terms, each score (and hence each rating) can be used more than once
- Robustness** - That quality of a problem solver that permits a gradual degradation in performance when it is pushed to the limits of its scope of expertise or is given faulty, inconsistent, or incomplete data or rules
- Rule** - A formal way of specifying a recommendation, directive, or strategy, expressed as *IF premise THEN conclusion* or *IF condition THEN action*
- Saturated Zone** - That part of an aquifer that is below the water table i.e. void spaces are full of water
- Scheduler** - The part of the inference engine that decides when and in what order to apply different pieces of domain knowledge
- Search Space** - The set of all possible solutions to a problem
- Semantic Net** - A knowledge representation method consisting of a network of nodes, standing for concepts or objects, connected by arcs describing the relations between the nodes
- Semi-Structured Interview** - An interview where specific questions are not developed beforehand but a set of topic areas for discussion are developed (interview schedule). Less formal than a structured interview but more formal and directed than an unstructured interview
- Soakaway** - System for allowing water or effluent to soak into the ground, commonly used in conjunction with septic tanks
- Source** - Point of pollution as in petrol-filling station or diffuse source as in agricultural run-off. Also point of abstraction of water e.g. well, spring, borehole
- Spring** - Natural emergence of groundwater at the surface
- Structured Interview** - A formal version of the interview in which the researcher plans and directs the session and has a prepared set of questions
- Symbol** - A string of characters that stands for some real-world concept
- Symbolic Reasoning** - Problem solving based on the application of strategies and heuristics to manipulate symbols standing for problem concepts
- Target** - Could include humans, fauna, flora, ecosystems etc. As in Source-Pathway-Target model, a target may be humans drinking polluted water or it may be groundwater itself that is polluted by a pollution source. It is the target which may suffer an adverse event (i.e. harm) and be at risk
- Unconfined Aquifer** - An aquifer in which the water surface is formed by the water table which is free to fluctuate under atmospheric pressure and can thus reflect changes in storage in response to abstraction and recharge
- Unsaturated Zone** - Zone of aquifer between soil and water table which is partly saturated (i.e. that part of the aquifer above the water table)
- Unstructured Interview** - Has no agenda (or at least no detailed agenda) set either by the researcher or by those being interviewed, there are no specific questions

**User** - A person who uses a knowledge system, such as an end-user, an expert, a knowledge engineer, or a support staff member

**Vadose Zone** - See Unsaturated Zone

**Water Table** - Top surface of the saturated zone within the aquifer (see Unsaturated Zone)



# CHAPTER 1

## 1 INTRODUCTION

### 1.1 RESEARCH CONTEXT

The subject of this research is the risk to the groundwater environment posed by point-sources of hydrocarbon pollution (such as petroleum from petrol-filling stations) and how this can be managed with the support of risk-based decision-making techniques. The focus is site prioritisation, as conducted by regulatory personnel (such as the Environment Agency in England and Wales). A knowledge-based approach presented via a computer system was developed to implement the knowledge obtained.

There is no one single definition of risk. Everyone is used to dealing with 'risk' by balancing the rewards of undertaking a risky activity with the possible adverse consequences. Fundamental to the concept of risk is that it is decision-making in the face of uncertainty (Adams, 1995: p1). It is apparent from the literature that decision-makers can be divided into two sectors: the formal risk experts, those who view risk objectively and seek to quantify, measure and reduce risk, the 'certified' risk experts and the informal 'non-certified' risk experts; members of the general public who do not quantify risk in a formal manner (Adams, 1995: p4). In 1983, the Royal Society (Royal Society, 1983: p22) defined objective risk as "the probability that a particular adverse event occurs during a stated period of time". The focus was on human health and 'measurable objective risk'. The Royal Society reported again on the subject of risk in 1992 (Royal Society, 1992), the difference between objective and subjective (or perceived) risk was maintained. The implication is that objective risk can be scientifically measured but that perceived risk can not and if it can not be measured it can not be a 'proper' risk. This view has been challenged by many authors and is discussed more fully in Chapter 2, when considering the psychological and socio-cultural influences on the perception of risk.

Risk as studied by the formal sector has traditionally encompassed 'human health risk' and in the United Kingdom (UK) has developed from the assessment of major accidents (HSE, 1989). In the United States of America (USA) however attention was focused on the control of chronic health risks (Petts & Eduljee, 1994: p116). Pollution is often conventionally seen in terms of harm to human health caused by man's activities and this is reflected in the traditional focus of risk to human health. Even if 'risk to the environment' is included, man is the ultimate focus. This anthropogenic focus can have implications for the way risk to the environment is perceived and managed.

Risk management as a process provides for a structured and logical way to identify, investigate and assess a risk (Petts, Cairney & Smith, 1997: p2). Inherent to the scientific view of risk is seeing risk assessment as a process separated out from risk management (the latter being a

legal, political and administrative task) (Royal Society, 1992). This view was echoed in guidance produced by the Department of the Environment on a risk-based approach to environmental protection (Department of the Environment, 1995a: p641). This separation may have led to too much emphasis on quantified risk assessment (Somers, 1995). Risk assessment and management is decision-making under uncertainty (Adams, 1995: p215) and understanding the impact of such uncertainties (on the environment or human health) relies upon scientific, technical *and* social value judgements. There is now acknowledgement that risk assessment is a mixture of science and policy (HSE, 1996a: p3) and that it does have a place, particularly in support of environmental regulatory activities (Ball, 1994).

It is the Environment Agency (in England and Wales) that is the regulatory body charged with protecting our environment, including the water environment. Taking a risk-based approach to environmental decision-making is an Agency objective (Environment Agency, 1997a: p25). Risk management (including risk assessment) is a structured process of hazard identification, hazard assessment, risk estimation, risk evaluation and management actions culminating in risk reduction. It is a complex process which is conceptually difficult to understand. The source-pathway-target model provides a framework for such risk-based decision-making (Lerner, 1997). This model has several advantages not least the provision of a rational overview of a problem (Loxham, 1992). However, sources, pathways and targets can be highly variable in nature and when assessing environmental risk, for example, to groundwater, there will be a large element of uncertainty.

The focus of this research has been on groundwater pollution and although groundwater can be seen either as a pathway or as a target it is often considered only as a target (particularly by regulatory bodies such as the Environment Agency). Groundwater is an important resource in the UK and elsewhere. It is significant not only as a human resource, but also as an important part of the natural environment. Groundwater is an intrinsic and fundamentally important part of the water cycle (Freeze & Cherry, 1979). It has several functions, for example, the provision of drinking water and the maintenance of base river flow (Environment Agency, 1998: p6). In the UK, approximately 30-35% of all water abstracted for drinking water is groundwater (Department of the Environment, 1996a; Harris, 1997). Other countries such as Denmark rely almost exclusively on groundwater as a source of drinking water (Price, 1996: p207). Unfortunately due to the location of such a resource, it is vulnerable to pollution: 'out of sight and out of mind'. The protection of groundwater purely as a water resource can be clearly demonstrated, however, mainly due to the nature of the resource, if it is polluted it can often be technically difficult and prohibitively expensive to clean-up (Harris & Skinner, 1992a; Roux, 1995). Thus, pollution prevention is preferable and it is by using a risk-based approach to groundwater protection and management that issues such as site prioritisation can be fully integrated into the regulatory decision-making process.

There are many substances with the potential to pollute groundwater, such as heavy metals, pesticides and hydrocarbons: as point or diffuse sources of pollution. Of the hydrocarbons, chlorinated solvents and petroleum hydrocarbons have presented a known point-source problem to groundwater in the UK for several years (e.g. Lerner *et al.*, 1993; Clark, 1995). The Environment Agency has recently published a report on point-source groundwater pollution (de Hénaut *et al.*, 1997) and at sites where groundwater contamination had been confirmed, hydrocarbons (such as petroleum), solvents and metals were the most frequently identified contaminants.

Petroleum hydrocarbons such as petrol and diesel are relatively insoluble in water and are termed light non-aqueous phase liquids (LNAPLs as opposed to DNAPLs such as chlorinated solvents which are denser than water) (Price, 1996: p253). Although overall solubility may be low, petroleum fuel is made up of a range of substances with a wide variety of solubilities, which can impact on groundwater (Cole, 1994: p76).

LNAPLs such as petroleum have also been responsible for several groundwater pollution incidents in the UK, particularly from underground storage tanks (Harris, 1993). This type of problem is not restricted to the UK and can be found in other industrialised countries such as France (Roux, 1995) and the USA (USEPA, 1988).

Petroleum hydrocarbons such as petrol and diesel present an almost ubiquitous risk to groundwater mainly due to the large number of potential sources (e.g. petrol-filling stations), the way such products are stored (usually in underground tanks) and the method of distribution (underground pipes). The structure and operation of a petrol-filling station is primarily governed by the fact that petroleum is a hazardous substance. Two Health and Safety Executive Codes of Practice are routinely used in the UK (HSE, 1990; HSE, 1996b) with non-statutory guidance being produced by bodies such as the Institute of Petroleum (e.g. IOP, 1995).

A typical retail petrol-filling station consists of several areas such as the fuel delivery, fuel storage and the fuel dispensing area. Fuel could be released into the environment at any stage. When considering a risk-based approach to assessing such a source all stages must be considered. For example, tank and underground pipework construction can have an effect on the risk posed to the groundwater environment but so can tank/pipework age, tank/pipework corrosion protection, type of leak detection system in use at the site etc. An apparently simple source such as a petrol-filling station is often deceptively complex when it comes to making environmentally protective decisions.

The study of groundwater pollution and protection is inherently tied into the way contaminated land has been viewed in the UK and how it has been dealt with in terms of government policy. In common with many industrialised countries, contaminated land per se is not a new problem

in the UK (Butler, 1996). In terms of groundwater pollution however, it is landfill sites which have been the focus of attention as pollution sources (e.g. Department of the Environment, 1978). Before the formation of the Environment Agency 'water issues' including groundwater were under the control of the National Rivers Authority (NRA) and the regional Water Authorities before that. Land quality issues were controlled by the local Waste Regulation Authority and Planning Authority. Historically there were no policy links between these bodies, which resulted in an uncoordinated approach to the management of contaminated land. Guidelines were issued by the government for the redevelopment of contaminated land (e.g. ICRCL, 1987) but there was no real attempt to identify sites that may be contaminated and may pose a threat to human health or the environment. Several other countries have adopted a more proactive approach to the problem e.g. the Netherlands (Vegter, 1993); Denmark (Poulsen, Vendelboe & Holm, 1993); Austria (Kasamas, 1994) and Canada (Hofmann *et al.*, 1993). In the UK, in addition to the political impact of major pollution incidents, such as Love Canal, another reason for the change from a reactive to a more proactive approach has been prompted by the concept of 'sustainable development'. The World Commission on Environment and Development defined sustainable development in 1987 as development that does not compromise the needs of future generations (World Commission on Environment and Development, 1987: p8). By 1992 a programme of action to achieve sustainable development had been agreed by the United Nations (Agenda 21 programme, United Nations, 1992). The 'precautionary' approach to pollution control is a fundamental principle of Agenda 21 and groundwater protection is recognised as an essential element of water resource management (United Nations, 1992: p172).

In legislative terms groundwater protection is governed by the European Directive 80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances and subsequent domestic legislation that enacted this Directive (such as Integrated Pollution Control under Part I of the Environmental Protection Act 1990, the waste management licensing regime under Part II and the consent to discharge matter into controlled waters under Part II of the Water Resources Act 1991). The Directive focuses on certain substances listed under 'List I' and 'List II'. The discharge of List I substances is prohibited and the discharge of List II substances is limited and must be authorised in some way. Mineral oils and hydrocarbons are List I substances.

In policy terms groundwater protection in the UK is governed by the Policy and Practice for the Protection of Groundwater which was originally developed by the Agency's predecessor body, the NRA (NRA, 1992). It has now been updated (Environment Agency, 1998). This policy promotes sustainable groundwater use, is risk-based in approach and was intended to support consistent decision-making. The policy has been implemented by the development of groundwater or source protection zones and groundwater vulnerability maps (NRA, 1995a; NRA, 1995b).

Point-sources of hydrocarbons such as petrol-filling stations are governed by the Policy and Practice for the Protection of Groundwater but it is not statutory. Specific statutory control is provided by the Petroleum (Consolidation) Act 1928 which allows for petroleum tanks to be licensed to store petroleum (not diesel). The licensing authority is usually the Fire Brigade but the focus is on health and safety not environmental protection so can not be relied upon to provide groundwater protection. Currently a new set of regulations proposed by the Department of the Environment, Transport and the Regions (DETR, 1998) is at the consultation stage. This will allow the Agency to "issue notices prohibiting or controlling activities in or on the ground involving List I or II substances..". These regulations as they stand would have an impact on a wide variety of industries and fuel storage is specifically mentioned in the consultation document.

It is clear that statutory control of potential sources of hydrocarbon groundwater pollution such as petrol-filling stations is not particularly co-ordinated in the UK. Various regulatory bodies may have an input to any one particular site e.g. the Environment Agency, environmental health officers and planning officers from the Local Authority, the petroleum licensing authority (usually the Fire Brigade), the Health and Safety Executive etc. This can lead to a conflict of interests or a lack of communication, increasing the chances of inconsistent or poor decision-making.

In other countries such as the USA this potential for inconsistent or poor decision-making has been identified. Groundwater is seen in the USA as a resource that requires strong protection from activities such as the underground storage of petroleum (USEPA OSWER, 1995). This resulted in a 'underground tank program' being set up to allow for the registration and inspection of sites. The regulations were designed to prevent, detect and clean-up releases where they do occur (USEPA, 1988). Risk-based decision-making forms a fundamental part of these regulations and how they are implemented by the United States Environmental Protection Agency, USEPA. Management techniques such as the ASTM standard Risk-Based Corrective Action (ASTM, 1995) were developed to promote efficient use of resources by focusing effort on the most high risk sites.

It is the widespread and the potentially serious nature of hydrocarbon pollution of groundwater, and the complex nature of any risk management process that pointed to a knowledge-based decision-support tool, as proposed by this research, to assist in that management.

In the UK in response to the UN Agenda 21 programme the government produced a sustainable development strategy (Anon, 1994a). The protection of groundwater from pollution is recognised (p62) as is contaminated land being a source of that pollution (p9). Contaminated land was the subject of a government consultation document 'Paying for our past' (Department of the Environment, 1994a). The outcome of this consultation, 'Framework for Contaminated

Land (Department of the Environment, 1994b) formed the basis for a more proactive approach to contaminated land management enacted by section 57 of the Environment Act 1995. This section inserts a new section 78A into the Environmental Protection Act 1990 and although based on the source-pathway-target model which is inherently risk-based, at the time of writing it has not as yet been implemented. As such, a co-ordinated and structured approach to contaminated land has taken several years to develop in the UK and is still evolving.

The Environment Agency (England and Wales) has the primary responsibility for groundwater protection and control of pollution, although it does not carry out that role in isolation from other regulatory bodies e.g. local authorities, or individuals. The concept of sustainable development is fundamental to Agency policies and objectives (Environment Agency, 1997a) including groundwater protection and the management of contaminated land and many of these policies are risk-based in nature. However, the Agency is a complex body and decision-making especially risk-based decision-making, which should be systematic, rational and transparent, can become difficult.

Groundwater pollution sources such as petrol-filling stations can be managed under the common framework of risk management but it is a complex process. An understanding of how a risk-based approach can be used with regard to point-source hydrocarbons can be gained by consideration of the historical development of environmental policy in the UK. In the past environmental management has been governed by a 'reactive approach' or on the basis of 'when the need arises (e.g. Petts, Cairney & Smith, 1997: p18). It is only recently that a more 'proactive' risk-based approach has been introduced. Such an approach needs to be based in the policies, functions and regulatory controls of the body charged with such duties i.e. the Environment Agency (for England and Wales).

A risk-based approach to decision-making has several advantages as it:

- is a systematic and logical process
- provides for consistent decision-making
- allows efficient use of resources by focusing on the higher risks
- supports a phased approach to problem-solving
- allows risk management actions to be prioritised

There are however, several disadvantages, which are particularly apparent in the regulatory context and these include:

- complex decisions have to be made across a wide variety of disciplines
- the availability of experts may be restricted

- decisions often have to be made quickly with a variable amount and quality of information
- the concept of risk is new to many within the regulatory environment

A large number of methods or tools have been developed to support risk-based decision-making ranging from qualitative assessment methods (e.g. McFarland, 1992) through to fully quantified assessment methods utilising, for example, complex fate and transport models (e.g. Ashley, 1994). However, almost without exception they fail in one or more respects - they usually require a high level of professional judgement on the part of the user and if computer-based, often a high level of familiarity with computers, i.e. an *expert* user. Many models are not designed with the potential end-user in mind with model assumptions for example, not being explicit and transparent to the user. User requirements and limitations if considered at all, feature at the end of the development process (e.g. Berry, 1994). One particular type of computer-based tool called expert or knowledge-based systems can be designed to be inherently user-focused.

## **1.2 RESEARCH OBJECTIVES**

It is proposed that using a knowledge-based system to support risk-based decision-making can go some way to supporting the advantages of risk-based decision-making and reducing the disadvantages. Knowledge systems can support the user without replacing their input and enable less experienced people to make decisions in a risk-based way.

Therefore the overall objectives for this research were:

- (i) to review the concepts of risk and risk management and its applicability to point-source hydrocarbon groundwater pollution;
- (ii) to identify and define the risks of contaminated or potentially contaminated sites with regard to groundwater pollution, and the information and assessment needs of relevant statutory bodies and industry, in relation to such sites,
- (iii) to review the application of knowledge systems for environmental decision-making in the UK and overseas;
- (iv) to identify key requirements for effective design and application of a knowledge system, and to identify the knowledge that is currently utilised by experts in groundwater protection to produce a conceptual model of that knowledge to determine if this approach is suitable;

- (v) to develop a prototype knowledge system capable of fulfilling some of those requirements identified in i to iv and that can act as a decision-support tool to assist in solving the complex problems often associated with groundwater pollution, to enable sites to be prioritised on the basis of risk to groundwater

Accordingly, this thesis is structured as follows. Chapter 1 introduces the subject and the thesis in general and the need for research in this area. Chapter 2 gives a review of risk, risk management and groundwater pollution, with a focus on the definition of risk and how risk can be managed. As an environmental risk, risk to groundwater is discussed, with a focus on the importance of groundwater as a natural resource and the sources of groundwater pollution. The concept of the source-pathway-target model and the risk-based approach to groundwater protection is introduced. Chapter 3 focuses on hydrocarbons and in particular petroleum hydrocarbons and their impact on the groundwater environment. Chapter 3 also includes a discussion of petrol-filling stations as point-sources of groundwater pollution. Chapter 4 discusses the risk management of hydrocarbons as point-sources of groundwater pollution in the context of past and current approaches to the problem, with a particular emphasis on policy development and regulatory controls. Risk management methods such as risk-based models are discussed and deficiencies in the current management methods identified. Chapter 5 discusses knowledge, expertise and knowledge systems. In particular, the definition of knowledge and expertise, how knowledge systems differ from conventional computer-based techniques and how such a system may support risk-based decision-making in a UK regulatory context. The chapter includes a discussion of current systems developed for use in the environmental field. Chapter 6 describes the system development process in detail, including initial problem definition, the identification of an expert and system user requirements. Tools and techniques that can be used for the knowledge acquisition and elicitation process are discussed. The elicitation methods used and the process of system development adopted for this research are described in Chapter 7. The results of the elicitation methods are described in Chapter 8 and how that information was utilised for system development is reported in Chapter 9. In Chapter 10 the results from Chapter 8 and the subsequent system that was developed (Chapter 9) are discussed. It is demonstrated how the research objectives ((i) to (v) above) have been achieved, conclusions drawn and suggestions made for the future direction of research in this area.



## CHAPTER 2

### 2 RISK, RISK MANAGEMENT AND GROUNDWATER POLLUTION

#### 2.1 THE RISK CONCEPT

##### 2.1.1 Definitions of Risk

'Risk' is defined by the Collins English Dictionary as "to expose to danger or loss; hazard". Everyone is used to dealing with 'risk' on a daily basis, crossing the road for example. We learn to balance the rewards of taking a risk with the possible adverse consequences. Fundamental to the concept of risk, however, is decision-making in the face of uncertainty (Adams, 1995: p1). Adams divides the decision-makers into two separate sectors. The *formal* sector consists of the 'certified' risk experts, those who seek to quantify, measure and reduce risk and are represented by government and those in authority. The *informal* sector consists of the 'non-certified' risk experts; ordinary members of the public who do not usually quantify risk in a formal manner but who make decisions and try to balance the risks. This dichotomy of the formal and informal approach to risk is often apparent in the literature (e.g., Royal Society, 1992).

The Royal Society report, 'Risk Assessment' published in 1983 (Royal Society, 1983) was a scientific review of the subject of risk. This report discussed two different types of risk - (i) 'objective risk', the risk assessed and studied by experts, the statistical probability of an event happening, and (ii) 'perceived risk', the view of risk of a non-expert i.e. an ordinary member of the public, a perceived probability of something happening which is not usually quantifiable. The Royal Society put forward a definition of objective risk as "the probability that a particular adverse event occurs during a stated period of time..." (p22). An 'adverse event' is one that produces 'harm' and harm was defined as a loss to a human being (or human population). The focus is very much on human health and 'measurable objective risk'.

Risk as studied by the formal sector has traditionally encompassed 'human health risk' but its application can vary, for example, the difference of approach between the UK and the USA. In the UK risk assessment developed from assessing major accident hazards or the acute immediate effects of the hazard (e.g. HSE, 1989). In the USA, attention was focused on regulatory control of chronic health risks (e.g. Petts & Eduljee, 1994: p116; Abernathy & Roberts, 1994). This has led to some confusion over definitions and approach. The various 'risk communities' use the same terms but with different meanings (McQuaid, 1995). In the area of health and safety regulation in the UK, a discussion document has been produced by the Health and Safety Executive that tries to clarify the situation (Le Guen, 1995). As yet there is no equivalent guidance relating to the environmental field although the Department of the Environment 'A Guide to Risk Assessment and Risk Management for Environmental Protection' (Department of the Environment, 1995a) does provide some definitions.

In 1992, the Royal Society produced another report on the subject of risk, entitled 'Risk: analysis, perception and management' (Royal Society, 1992). This report discusses the 'perception' of risk but still tries to maintain the difference between scientific, objective risk and subjective or perceived risk. This view is widely held in the UK and elsewhere (e.g., National Research Council, 1983 as referenced by Somers, 1995). The outcome of this view is that objective risk can be scientifically measured and that subjective or perceived risk can not. The key word here is 'measured', implying that if it can not be measured it can not be a 'proper' risk and is therefore irrational. This view is not accepted in the social sciences and is challenged by many authors (e.g. Douglas & Wildavsky, 1982; Schwarz & Thompson, 1990; Adams, 1995).

This concept of perceived risk has been discussed extensively in the literature and which factors may contribute to risk perception have been investigated by several authors (e.g. Slovic, Fischhoff & Lichtenstein, 1980; Douglas & Wildavsky, 1982; Slovic, 1987; Covello, 1991). This has been carried out often on the basis of:

- psychological influences and/or
- social and cultural influences on the perception of risk

The psychological basis for the perception of risk is thought to underlie the 'difference' in the way experts and the public perceive risks and what is an acceptable risk i.e. the way people make risk judgements (Tversky & Kahneman, 1974). Factors that were found to be important in the way risk is perceived included (e.g. Fischhoff *et al.*, 1981; Slovic, 1987; Covello, 1992; Slovic, 1993):

- level of familiarity (of the technology for example)
- level of uncertainty (how well are the risks known)
- level of control (how much control has the individual have over the process)
- level of equity (is one community expected to take all the risks whilst another gains all the benefits)
- level of trust (do individuals trust the company or institution building a new incinerator for example)
- level of reversibility (are the benefits clear and effects reversible)
- whether children were specifically at risk (or future generations)

In addition to the psychological risk literature, there is also a significant amount of work investigating the theory that risk can also be socially and culturally constructed, based on 'Cultural Theory'. What beliefs people hold about nature and the world, shape the way they perceive risk (whether they are a risk 'expert' or an ordinary member of the public) and which risks they consider acceptable and which ones are unacceptable (Thompson, 1980; Douglas & Wildavsky, 1982: p14).

### 2.1.2 The Cultural Theory of Risk and Risk Management

In the late 1970's and early 1980's ecologists studying the management of ecosystems put forward the idea that the management strategy adopted will be based on one of four interpretations of ecosystem stability or 'myths of nature' (Schwarz & Thompson, 1990: p4; Thompson, Ellis & Wildavsky, 1990: p26). Much ecological research had already been carried out into anthropogenic effects on ecosystems, for example, the effect of raised copper levels in the soil due to copper mining was demonstrated by measuring the number of grass species that would grow in copper contaminated soil. At high copper concentrations very few individuals of any species survived apart from one that was 'tolerant' to copper. As soil concentrations fell with time, more species were able to survive but the range of species was much smaller than would have been present without the copper pollution (Begon, Harper & Townsend, 1986: p70). The key point is, that with time the soil was not bare of vegetation but the 'new' ecosystem was species-poor, has nature 'recovered' or been damaged beyond recognition?

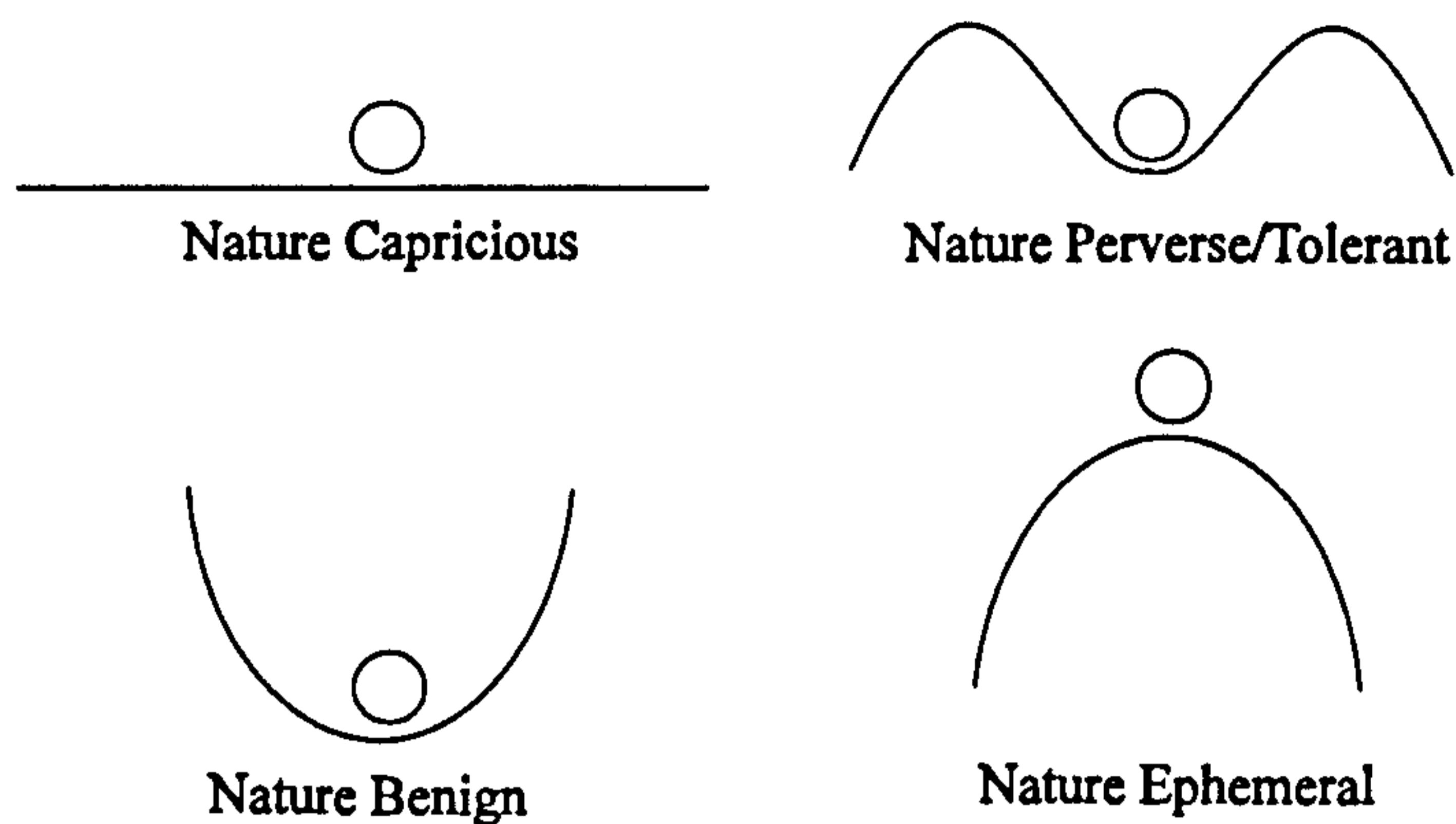
The 'myths of nature' describe four different 'belief systems' about how people perceive nature will respond to interventions in those systems. When an ecosystem manager has to make a decision, often with insufficient information, they assume nature will behave in a certain way - the 'myths of nature', shown in Figure 2.1 (Schwarz & Thompson, 1990: p5; Adams, 1995: p33).

*Nature benign* - nature is forgiving, stable and robust, no matter what man does to the environment the ball will always return to the bottom of the basin. Management can therefore be very relaxed and 'non-interventionist'.

*Nature ephemeral* - nature is not forgiving, it is fragile and subject to catastrophic collapse. Environmental management must protect nature from humans, embodied by the 'precautionary principle'.

*Nature perverse/tolerant* - nature is forgiving of the majority of events but can be vulnerable to the occasional knock. Management requires some regulation to prevent 'major excesses' but the system looks after itself for the rest. Management is 'interventionist'.

*Nature capricious* - nature is a random event and behaves unpredictably. Management is really 'non-management' as there is no point to managing the system.



**Figure 2.1:** The four primary myths of nature (Thompson, Ellis & Wildavsky, 1990): p27)

Each management style looks irrational to holders of the other three styles, whilst looking perfectly rational to the holder of that management style and that belief. These belief systems do not only apply to ecologists, for example, a multinational company may view 'environmentalists' as irrational because they campaign against what the company sees as minor risks but ignore major risks. Authors such as Schwarz & Thompson (1990) and Thompson, Ellis & Wildavsky, (1990) have linked the idea of the myths of nature with an anthropological typology of social relationships to constitute a 'Cultural Theory' of behaviour. The way an individual sees themselves and how they see their relationships with others will affect their decision-making behaviour (including decisions about risk). The four types (Figure 2.2) are described by Schwarz & Thompson (1990: p7 & p66) as:

*Individualists* - people who seek to control others and the environment they operate in, they learn by trial and error and believe in 'opportunity for all'. They concentrate on the short-term and the 'bottom line'.

*Hierarchists* - people with strong group boundaries, with everyone knowing their place in the structure. They try to anticipate events and balance short-term and long-term goals with the law providing equality.

*Egalitarians* - people with strong group boundaries who value co-operation but who do not respect externally imposed rules/laws (apart from nature). They aim to learn by trial but without error and the long-term outcome dominates the short-term. Equality is represented by outcome i.e., you reap what you sow.

*Fatalists* - people with little choice in their lives, marginal members of society who have no influence over events, 'life is a lottery' and there is nothing you can do about it. There is no equality.

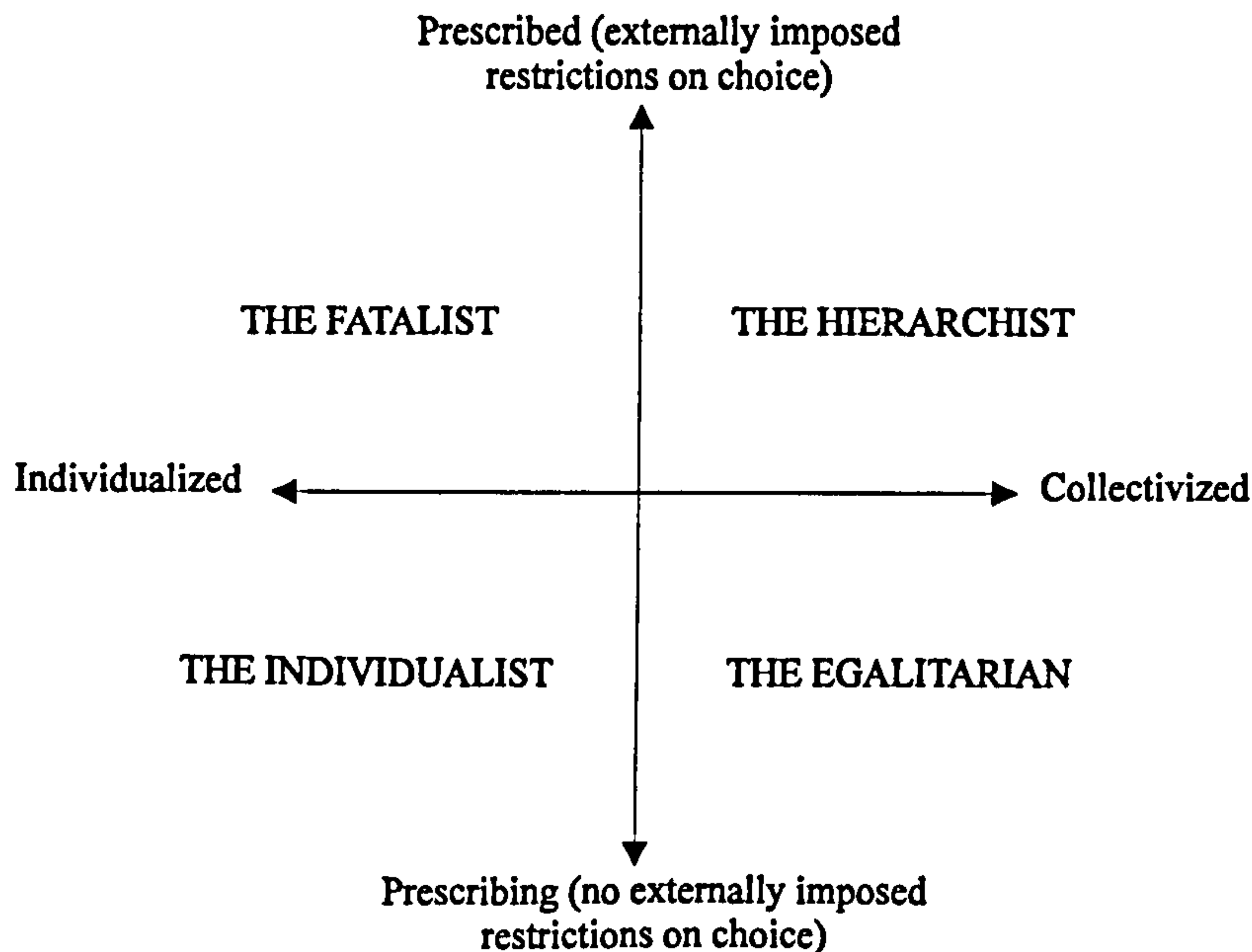


Figure 2.2: The four myths of human nature (Schwarz & Thompson, 1990: p7)

By linking the anthropological (human) and the ecological (physical), four 'world views' or rationalities of life can be generated (Adams, 1995: p37) shown in Figure 2.3. For example, the egalitarian view of life is that 'small-is-beautiful' and nature is fragile and ephemeral and requires protection, typified by Schumacher (1973: p136): "The system of nature, of which man is a part, tends to be self-balancing, self-adjusting, self-cleansing...not so with man dominated by technology. Technology recognises no self-limiting principle...in the subtle system of nature, technology...acts like a foreign body, and there are now numerous signs of rejection".

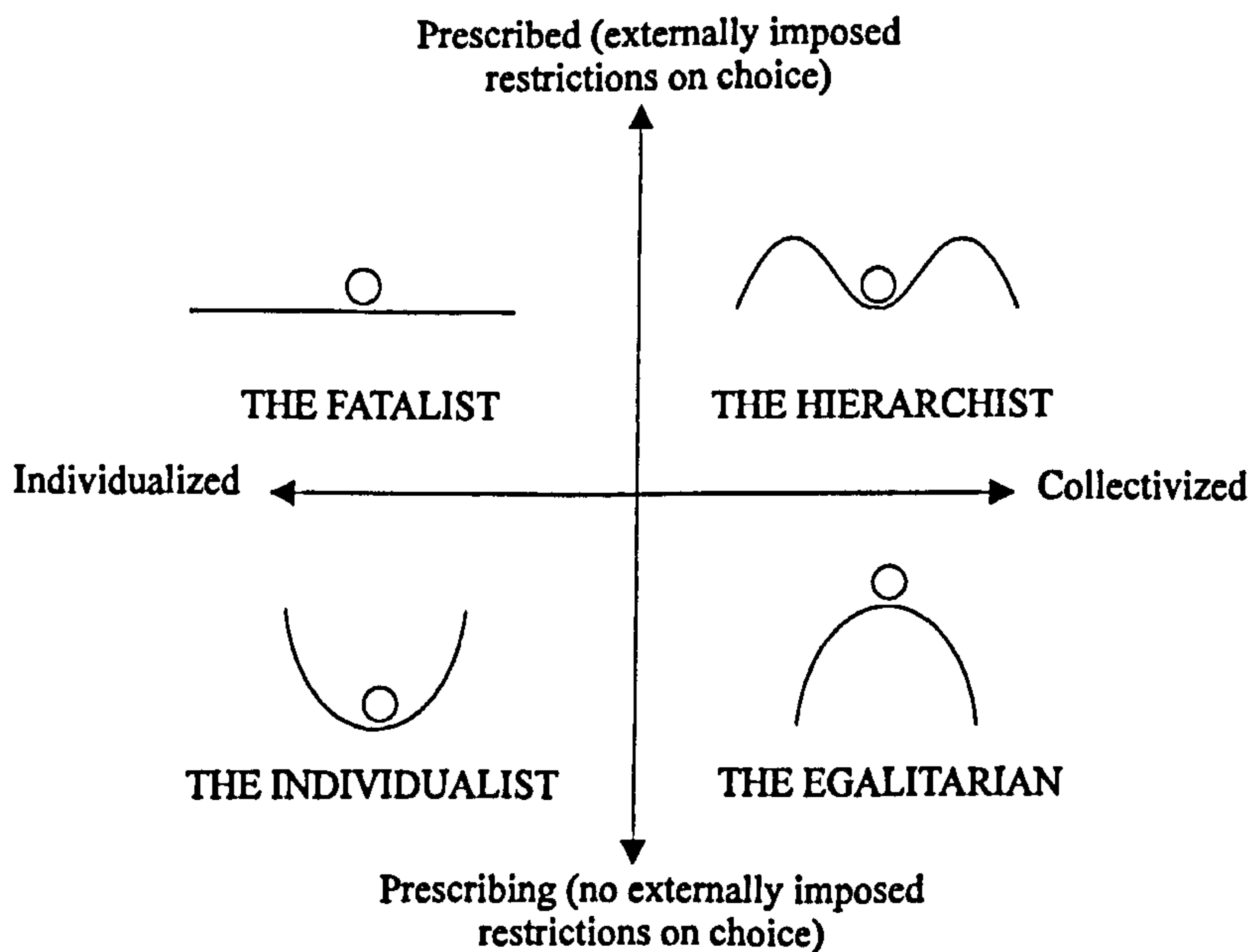


Figure 2.3: The myths of nature mapped onto the myths of human nature - the four rationalities (Schwarz & Thompson, 1990: p9)

Thompson, Ellis & Wildavsky (1990) actually describe a fifth type of human nature they call the 'hermit' (p29). The hermit withdraws from all social involvement but a hermit way of life is only viable if all the other four ways of life are present for the hermit to withdraw from. The hermit way of life has its own myth of nature and that is 'Nature Resilient' which transcends all the other four myths of nature as the hermit way of life transcends the other four ways of life (hierarchist etc.). Nature as resilient accepts that the world can change from one 'mode' to another. Using the ball in the bowl 'landscape' example (Figure 2.1) and nature starting out as tolerant/perverse, managing a system be it the whale population, or the global atmosphere means keeping the ball in the tolerant zone. This works until the bowl which has got shallower, flattens out and turns into a bump, nature is then perverse and the system has 'flipped' to 'nature ephemeral'. This view of nature as a dynamic system is perhaps close to that described by James Lovelock in his Gaian hypothesis. The Gaian hypothesis proposes that "the physical and chemical condition of the surface of the Earth, of the atmosphere, and of the oceans has been and is actively made fit and comfortable by the presence of life itself" (Lovelock, 1987: p152). Humans are but a partner in the whole entity (Lovelock, 1987: p145).

Pollution is often conventionally seen in terms of harm to human health caused by mans activities, this is reflected in the traditional focus of risk as ultimately risk to human health, even if 'risk to the environment' is also considered, for example, risk to groundwater. Following the Gaian hypothesis, human activity may have the ability to upset the system but "there is only one pollution....People" (Lovelock, 1987: p122). The Gaian hypothesis is not anti-technology and Lovelock (1987: p117) promotes the idea of using technology to 'monitor' human effects on the world and to engender a more harmonious partnership. Studying and controlling the effects of pollution from such a wide (non-human) perspective is still reliant on our own belief system and comes back to the cultural theory of risk and what is or is perceived to be an 'important' risk and what is not.

The cultural theory of risk is just that, a theory but has been used by Douglas & Wildavsky, (1982) and Adams, (1995: p40) to try and explain why disputes over the environment occur with each 'side' accusing the other of irrationality and subjectivity and why risk is managed at all. Indeed some authors state that there is very little evidence that cultural theory of risk can explain risk perception in a quantitative sense (e.g. Sjöberg, 1997) . However, the cultural theory of risk still provides a useful and interesting 'framework' to place risk assessment and risk management, especially within a regulatory environment, even if it can not be 'proved' quantitatively.

In terms of 'risk' to the environment, an individualist will see no risk associated with an activity, until there is scientific proof of harm being caused by it and therefore no reason to intervene or manage the environment until that time. The egalitarian will apply the 'precautionary approach' and only allow the activity when there is proof that harm will not be caused. The hierarchist

will believe that the risk can be managed by, for example, regulation and there may be benefits in allowing the activity to take place as well as risks to be considered.

The 'activity' in question could be the use of petroleum hydrocarbons as in a petrol-filling station sited close to a major public water supply borehole. The individualist could be represented by those who own the petrol-filling station and are selling their product to the public. The egalitarian is the environmental pressure group campaigning to close the site due to fears that the local drinking water will be contaminated. The hierarchists could be represented by the local authority who gave planning permission for the site and the Environment Agency who has a duty to protect the environment. The 'cultural theory of risk' is a 'black and white' representation, but in reality the situation is complicated by the fact that people can be worried about their drinking water being contaminated and support the egalitarian view of the precautionary principle and shut the site until it can be proved that their water is not affected but also adopt a more individualist approach as the site is also the nearest petrol station and they want to be able to get their petrol as and when they need it. The hierarchists try to balance the risks posed to the environment and to human health by managing that risk. Currently, the way to manage that risk is to measure it and carry out some form of risk assessment. This comes back to the differentiation of 'objective' and 'perceived' risk, discussed at the beginning of this section and what is an acceptable and an unacceptable risk. The level of risk is only one among several variables that determines acceptability (Covello, 1992).

### **2.1.3 Risk Assessment v Risk Management**

Inherent to the scientific view of risk is seeing risk assessment as a process separated out from risk management, which is seen as a legal, political and administrative task (Royal Society, 1992: p136). Risk management is defined as "the process whereby decisions are made to accept a known or assessed risk and/or the implementation of actions to reduce the consequences or probabilities of occurrence" (Royal Society, 1992: p5).

Guidance produced by the Department of the Environment (1995a: p39) on a risk-based approach to environmental protection also separates out risk assessment from risk management. This view does not have universal support (e.g. Silbergeld, 1991; Petts, Cairney & Smith, 1997: p27). A report produced by the UK's Interdepartmental Liaison Group on Risk Assessment acknowledges that risk assessment is in reality a mixture of science and policy (HSE, 1996a: p3). Somers (1995) stated that this distinction between objective (scientific) and subjective (social/political) management of risk, has led to "a too mechanistic approach to decision-making whereby too great an emphasis is placed on quantification".

Risk assessment and management is decision-making under uncertainty, as Adams (1995: p215) states "they are all guessing; if they knew for certain, they would not be dealing with risk".

Understanding the impact of these uncertainties (on human health and/or the environment as a whole) relies upon scientific, technical and social value judgements. This was recognised in the USA by 1979 in relation to human health (Rowe, 1980) as was, the idea that if risk assessment was to support decision-making "it must be seen as part of a more comprehensive analysis, rather than a separate tool" (von Winterfeldt, 1980). However, the regulatory approach taken by the United States Environmental Protection Agency (USEPA) has relied heavily on quantitative risk assessments with a focus on carcinogenic substances and extrapolation of animal data to humans (National Research Council, 1983, as referenced by Somers 1995). The reliance on animal toxicological data has been attacked in it's own right as falsely increasing confidence in quantitative risk assessments (e.g. Taylor, Evans & McKone, 1993; Furst, 1994).

There is at least recognition from Central Government in the UK, that risk assessment does have a place, particularly in support of regulatory activities in the area of health, safety and the environment (Ball, 1994). The Government seeks to reduce risks and to "reduce inequities in the distribution of the risks and benefits between different sectors of the population ... and between humans and the natural environment" (McQuaid, 1995). McQuaid also states that poor regulation can lead to excessive costs for industry, needlessly restrict individual freedom and stifle innovation and that using a risk-based approach to decision-making will lead to better regulation.

The view that risk is not just a scientific measurement but is socially and culturally constructed is gradually gaining acceptance, and although perhaps not officially discussed in detail, at least there is acceptance that risk is something more than just 'science' (e.g. HSE, 1996a: p3). There must be an understanding that our own beliefs, how we behave and what we, as members of the public 'see' as important risks e.g., risk to our drinking water or risk to flora/fauna, has an impact on our risk management strategies. There is a 'moral' decision to be made - is risk only about humans and their place in the world and about proving (or not) that there is harm to human health or is it about more than that, moving in to the field of ecological risk and a responsibility towards the environment in it's own right? The 'moral' dilemma is between two potentially opposing views: (i) anthropogenic, which focuses on risk to humans and (ii) ecological, which focuses on the protection of the environment, although still including humans (e.g. Wildavsky, 1995: p446).

The Environment Agency is the regulatory body charged with protecting our water environment (in England and Wales) but one of the strategic objectives of the Agency is "to work with all relevant sectors of society, including regulated organisations, to develop approaches which deliver environmental requirements and goals without imposing excessive costs (in relation to benefits gained) on regulated organisations or society as a whole" (Environment Agency, 1996a: p9). In addition, the Agency is made up of individuals, each with their own 'risk agenda'



or what they see as important professionally. By understanding that risk can be culturally constructed and as individuals we can hold widely differing 'world-views', ensures a truer understanding of a risk-based approach to decision-making. This is a critical point in understanding risk to groundwater from point-source hydrocarbons and in understanding the decision-making process surrounding the management of such a risk by the Environment Agency or even why it should be managed at all.

#### 2.1.4 Managing Risks - The Process

In order for a risk to be managed successfully, it must be identified, investigated and assessed in a structured and objective way - this can be represented by the risk management framework shown in Figure 2.4 (Petts, Cairney & Smith, 1997: p2).

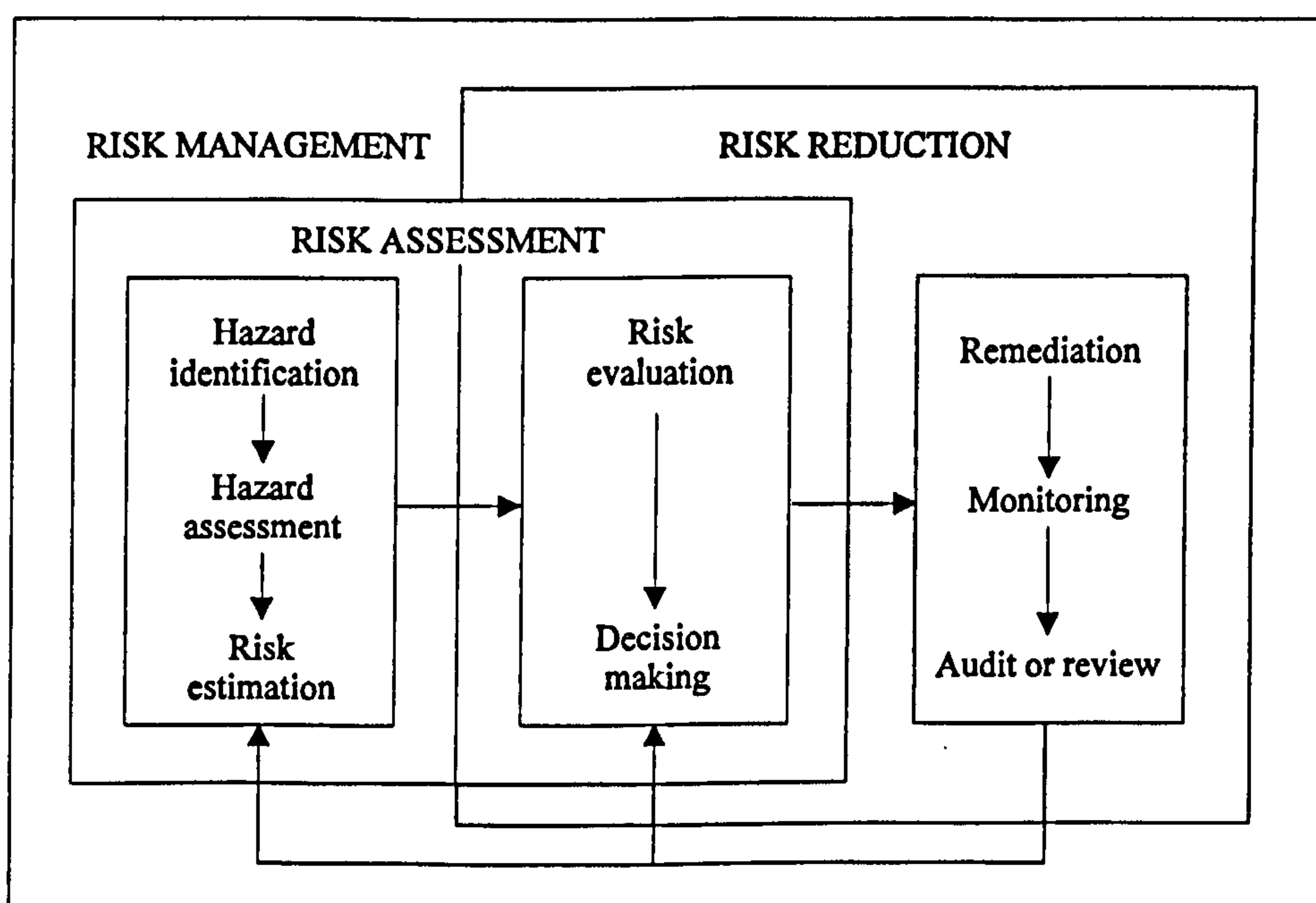


Figure 2.4: The risk management framework (Petts, Cairney & Smith, 1997: p2)

The risk assessment stage is a fundamental part of the overall risk management process and includes (Petts, Cairney & Smith, 1997: p30):

- identification of the hazard (what is the source of the pollution?)
- hazard assessment (what might happen to any potential targets?)
- estimation of the risk (probability that the hazards will occur and magnitude of the effects?)
- evaluation of the risk (is the risk acceptable?)

A hazard has been defined in terms of industrial risk as "the disposition of a thing, a condition or a situation to produce harm". The term 'disposition' describes properties intrinsic to a hazard and which under certain conditions are harmful (Le Guen, 1995).

Harm has been described by the Royal Society (1983: p22) in terms of risk "as the probability of an adverse event occurring in a stated period of time and an adverse event is one that causes harm to humans". This view of 'harm' was widened in the Environmental Protection Act, 1990 (Part II, section 29) to include "harm to the health of living organisms or other interference with the ecological systems of which they form a part and in the case of man includes offence to any of his senses or harm to his property". It is this definition of harm that is used as a basis for the new definition of contaminated land in the Environment Act, 1995 (where section 57 of that act inserts a new part into the Environmental Protection Act, 1990, entitled 'Part IIA - Contaminated Land', section 78A to 78YC).

The term 'pollution' requires some clarification. Holdgate (1979: p17) defined pollution as "The introduction by man into the environment of substances or energy liable to cause hazards to human health, harm to living resources and ecological systems, damage to structures or amenity, or interference with legitimate uses of the environment". The causation of harm is implicit in the definition of pollution. The Royal Commission on Environmental Pollution (RCEP) in their 10th report (RCEP, 1984: p3) supported the view that there is a difference between 'contamination' and 'pollution'; the former being the presence of a foreign substance which may or may not cause harm but the latter implying that harm is caused. This report also supported Holdgate's definition of pollution.

The focus of this research has been on groundwater *pollution* caused by point-source hydrocarbons such as petroleum being release into the ground from retail petrol-filling stations. The presence of a petrol-filling station on a piece of land does not necessarily mean that land is contaminated or polluted. In order for land to be considered as 'contaminated land' under section 78A of the Environmental Protection Act, 1990, it must be causing or have the potential to cause 'significant harm' or 'pollution of controlled waters'. However, it is this second parameter that has significance for groundwater in terms of risk. The Water Resources Act, 1991 definition of 'controlled waters' includes 'inland freshwaters' (watercourses, lakes etc.) and groundwater (Mumma, 1995: p24). The pollution of controlled waters means the "entry into controlled waters of any poisonous, noxious or polluting matter or any solid waste matter" (Environmental Protection Act 1990, section 78A (9)).

The contaminated land regime as laid out in the Environment Act is discussed further in Chapter 4, as is the actual risk management process and particularly risk assessment as related to groundwater pollution.

### 2.1.5 Source-Pathway-Target Model

The basis of a risk-based approach to groundwater protection is consideration of the 'Source-Pathway-Target' model which provides a framework for risk-based decision-making. In order to assess a situation all three elements must be considered (Lerner, 1997). This model can be used to represent a variety of different sources, pathways and targets and is not exclusive to the groundwater issue, Figure 2.5 illustrates some examples but is simplified in that indirect pathways are not included. Loxham (1992) states that the model can provide:

- a rational overview of the problem
- support for designing cost effective investigations
- support for choice of remediation action
- long term predictions of site behaviour

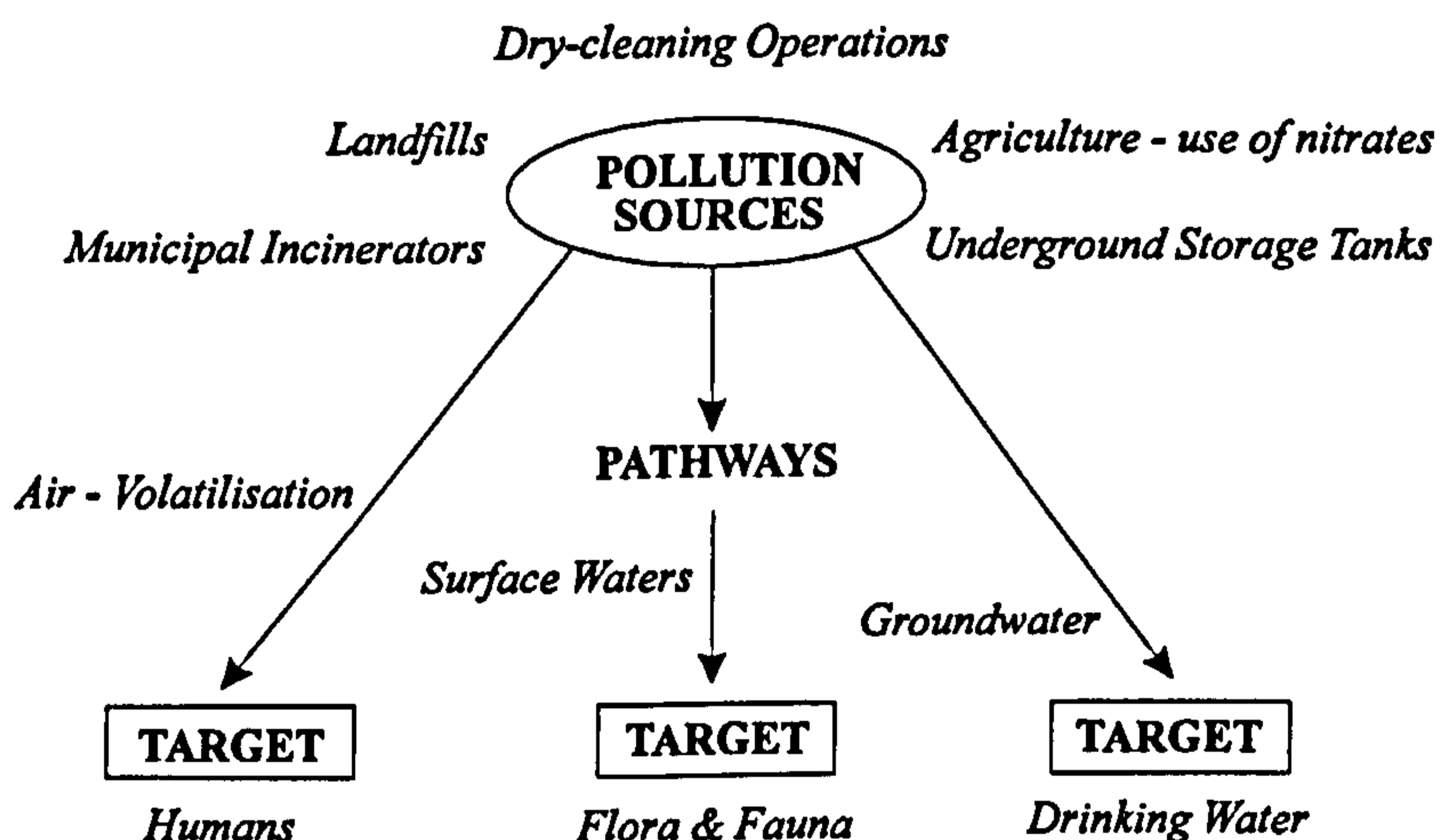


Figure 2.5: The Source-Pathway-Target model.

Sources of potential groundwater pollution are extremely varied and are discussed in more detail in section 2.2.3 and hydrocarbon sources in particular in Chapter 3. Groundwater itself can be seen as the pathway element, allowing transport of contaminants from the source to the target (e.g. humans) but it is usually seen as the target (e.g. EC Directive 80/68/EEC and the Waste Licensing Regulations SI 1056, regulation 15). For example, groundwater can be seen in terms of contaminated base flow for rivers, or as a drinking water resource. Targets can be highly variable in nature and are not restricted to those that may have potential human health impacts. Targets could include drinking water supplies (surface and groundwater) agricultural abstractions, industrial abstractions and wetland habitats.

Much of the information required to be able to use a source-pathway-target model when assessing risk to groundwater has a large component of uncertainty. The answers to questions asked may not be known at all or only partial answers can be provided (Reichard *et al.*, 1990:

p5). Table 2.1 illustrates some of the information that is necessary when assessing risk to groundwater with each question often providing an element of uncertainty.

**Table 2.1:** The source-pathway-target model and risk to groundwater - information requirements and areas of potential uncertainty (Reichard *et al.*, 1990: p6)

Element of Model	Information Required
<i>Source</i>	Will pollutants be released into the environment? When will a release occur and for how long? Which pollutants will be released? How much will be released?
<i>Pathway</i>	Will pollutants be able to reach a target? When will pollutants reach the target? Which pollutants will reach the target? How much will reach the target?
<i>Target</i>	What are the targets? How will the target be affected? Can the target be protected in any way?

The essence of the source-pathway-target approach to risk-based decision-making is the consideration of all the elements together and not in isolation from one another. The element often considered first however, is the source of the pollution (Reichard *et al.*, 1990: p11). The focus of this research has been petrol-filling stations as point-sources of hydrocarbon groundwater pollution. The remainder of this chapter describes what 'groundwater' is, what it is used for and how it can be affected by sources of pollution. The following chapter discusses in more detail petroleum hydrocarbons as a source of groundwater pollution.

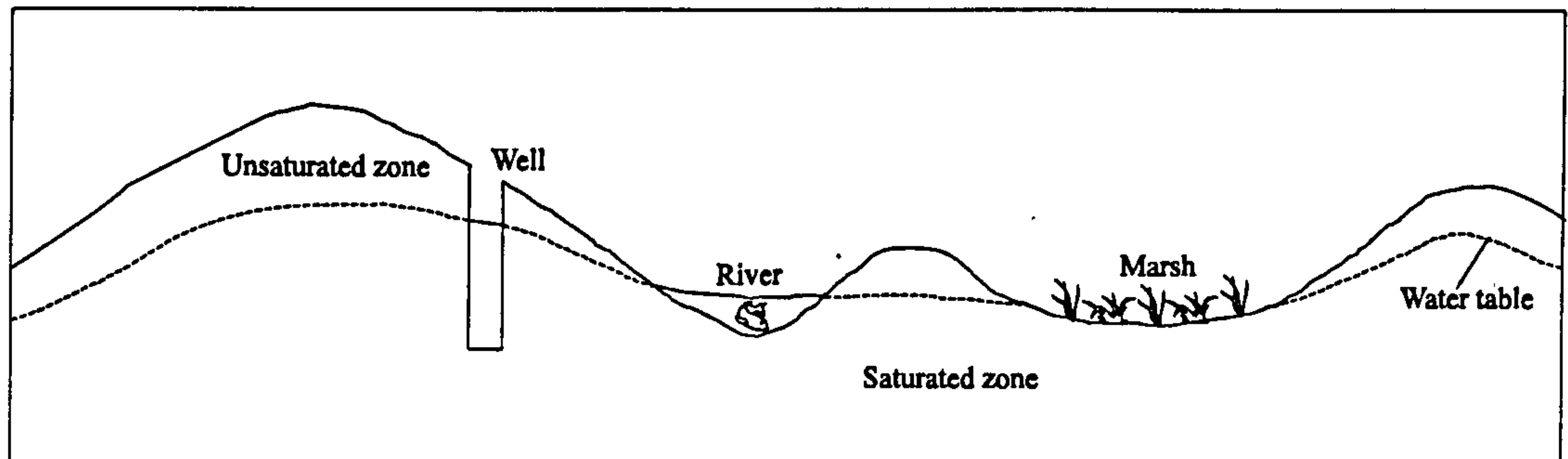
## 2.2 RISKS TO GROUNDWATER

### 2.2.1 Definition of Groundwater

In order to fully understand what 'groundwater' is, it is necessary to consider 'water' and 'ground' in general terms. Irrespective of soil or building cover at the land surface, the sub-surface consists of rock, which varies spatially by type. The significant characteristic of this sub-surface, important to the consideration of groundwater, is the size and shape of the rock pores. Rock types with a large proportion of pores e.g., chalk, exhibit high porosity.

Soil itself is porous and the moisture level usually increases with depth. Pores becoming partially and then completely filled with depth through the soil/rock matrix. This denotes movement from the unsaturated to the saturated zone, the unsaturated zone being the portion of the soil/rock matrix where the pores are not filled with water. The interface of these two zones is termed the water table. The water table is not at a constant level across the UK or even at a single point, the level can rise and fall, tending to mirror the land surface: i.e., being further from the surface under hills and closer to the surface under valleys (Figure 2.6). The layer of rock immediately above the water table is called the capillary fringe where water is held by

capillarity (Price, 1996: p25). This layer can also rise and fall but is not completely saturated with water, and this can have implications for how contaminants such as petroleum move from the unsaturated to the saturated zone (e.g. Chapter 3, Figure 3.1).



**Figure 2.6:** Diagram illustrating the unsaturated zone, saturated zone and the water table (Price 1996: p7)

Water that occurs naturally below the land surface is called 'sub-surface water' and can be found in the saturated and unsaturated zones. Water contained in the saturated zone, i.e., below the water table is termed 'groundwater' (Price, 1996: p7). It can also be defined in a slightly different way as "subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated" (Freeze & Cherry, 1979: p2).

Three factors affect the distribution and hence availability of groundwater: porosity; permeability and replenishment. Porosity is defined as the ratio of the volume of the voids (pores) in a rock to the total volume of the rock. Some rock types have only a few small pores reducing the available space that water can fill. The size of the pores combined with the level of interconnection between the pores, is termed the permeability of the rock and affects how easily water can flow through it. A rock can be porous but relatively impermeable if the pores are very small, or not connected and vice versa. A rock that is porous enough to store water and sufficiently permeable to allow water to flow through it in economic quantities is called an aquifer (Price, 1996: p9). Again, the term aquifer, like groundwater has more than one single definition, for example, the word 'economic' in Price's definition is substituted by 'significant' in Freeze and Cherry's (1979: p47). The third factor influencing the distribution of groundwater is the 'rate of replenishment': i.e. the level to which water that has been removed is replaced. This can come from a variety of sources, such as precipitation or adjacent aquifers. The level of replenishment depends on the nature of the rocks, soil type, level of vegetative cover, precipitation etc. and it forms part of the water balance of an area.

The definitions discussed above are not used exclusively. In 1980, the European Commission published a 'Groundwater Directive' (80/68/EEC) on "the protection of groundwater against pollution caused by certain dangerous substances" (such as heavy metals). Groundwater was defined for the purposes of the Directive as "all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil".

The Environment Agency (England and Wales) uses the definitions of its predecessor body, the National Rivers Authority and defines groundwater as the water found in rocks called aquifers and aquifers are strata that contain groundwater in exploitable quantities for any use (Environment Agency, 1998: p20). The term aquifer has also been defined as "permeable strata that can transmit and store water in significant quantities" (NRA, 1995b: p46). Aquifers are further subdivided into (Harris & Skinner, 1992a; Environment Agency, 1998: p20):

- Major aquifers - highly permeable, often fractured strata, capable of having water pumped from them in large quantities for public supply and other uses (strategically important for water supply)
- Minor aquifers - fractured (or potentially fractured) which do not have a high permeability or other strata with variable permeability, important for local supply and supplying base flow to rivers
- Non-aquifers - not very permeable, do not contain groundwater in exploitable quantities but groundwater flow does take place at a slow rate (important when considering risk to groundwater, especially from persistent pollutants)

In England and Wales the most important aquifer in terms of water abstraction is the Chalk aquifer, which provides approximately 54.5% of groundwater, followed by the Permo Triassic Sandstones (26%) and minor aquifers such as the Lower Greensand (19.5%) (Sir William Halcrow and Partners Ltd, 1988: p14).

The Groundwater Directive and the more limited (but pragmatic in resource management terms) approach taken by the Environment Agency for groundwater protection in England and Wales is discussed further in Chapter 4, section 4.2. Such differences in definition must be taken into account when the risks to 'groundwater' are assessed: the terms 'groundwater' and 'aquifer' do not always have the same meaning.

### **2.2.2 Groundwater as a Resource**

Groundwater can not be considered in isolation from other water sources, it forms a fundamental part of the water cycle. However, the very nature of groundwater can make it vulnerable to pollution: i.e. it is below ground and somewhat 'out of sight, out of mind' (Environment Agency, 1998: p6).

Groundwater is significant not only as a human resource, but also as an important part of the natural environment and as a fundamental part of the hydrologic or water cycle (Freeze & Cherry, 1979: p3). The total amount of water on the Earth is estimated as 1400 million km<sup>3</sup>, 95% of this being sea water, 2% is in glaciers and icecaps and most of the remaining 3% is groundwater. Water in rivers, lakes, the atmosphere and the unsaturated zone only makes up

0.02% of the total of all water (Price, 1996: p7). Estimations of global groundwater vary, but it is judged that 700 billion m<sup>3</sup> are withdrawn annually from aquifers (Roux, 1995) it is clearly an important resource. This can be demonstrated by groundwater abstraction and use data.

Figure 2.7 illustrates the variation in use of groundwater as part of public drinking water supply across Europe. Some countries e.g., Switzerland use a particularly high percentage of abstracted groundwater for drinking water. Figure 2.8, illustrates groundwater abstractions as a percentage of total water abstractions. Using Switzerland as an example, groundwater forms 81% of total water abstracted and is an essential water resource for that country.

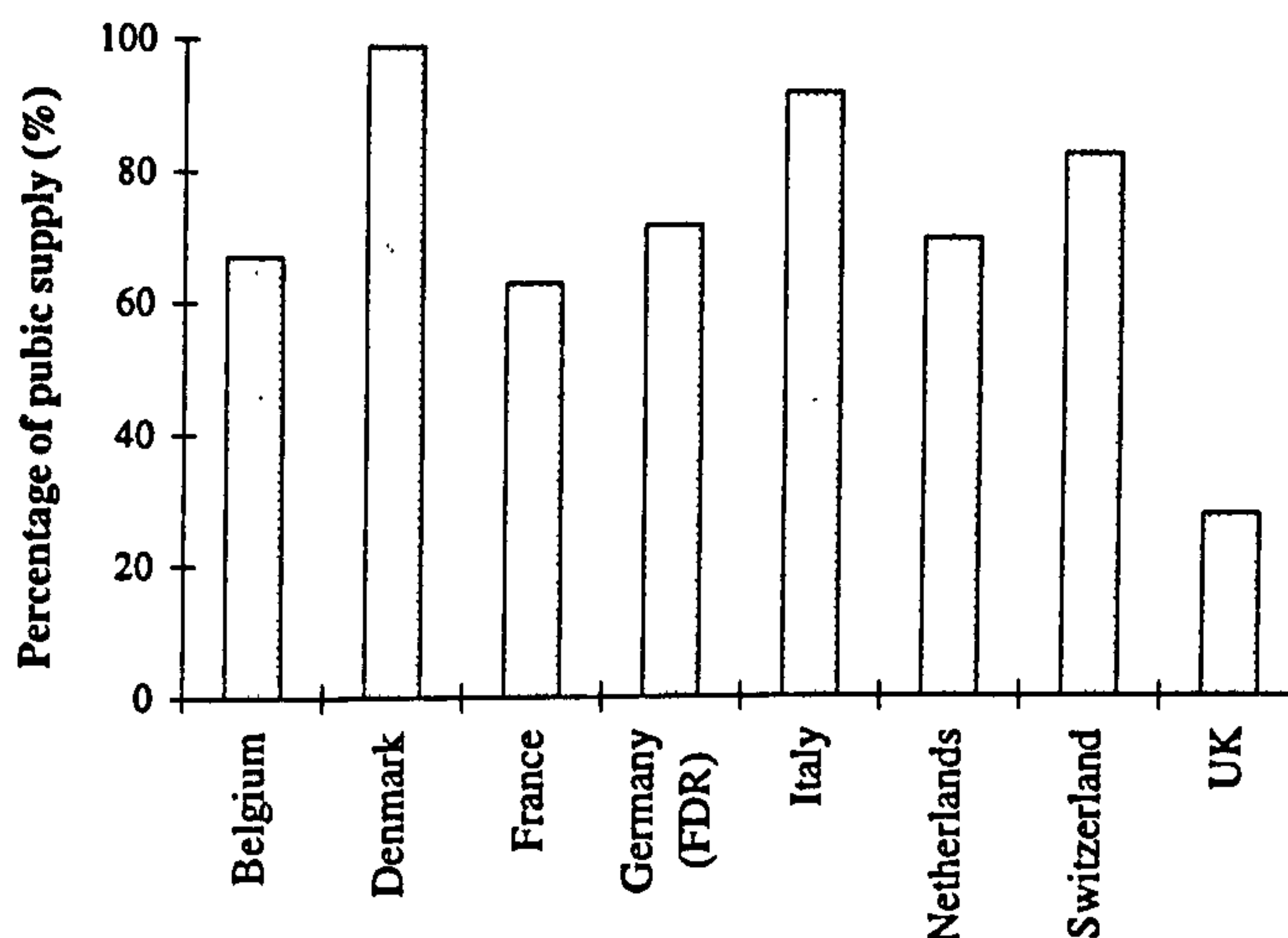


Figure 2.7: Groundwater use for public supply across Europe in 1986 (Price, 1996: p207)

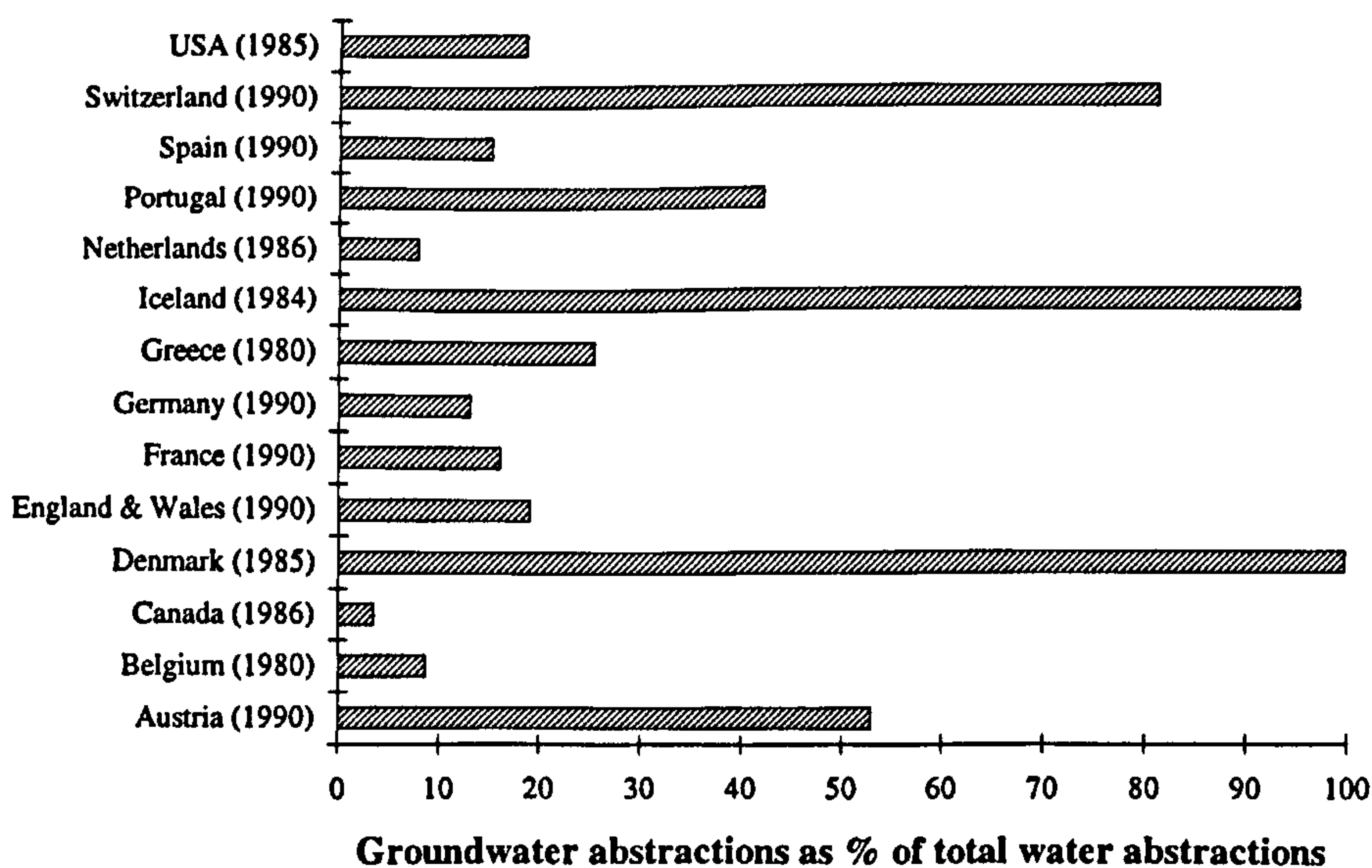
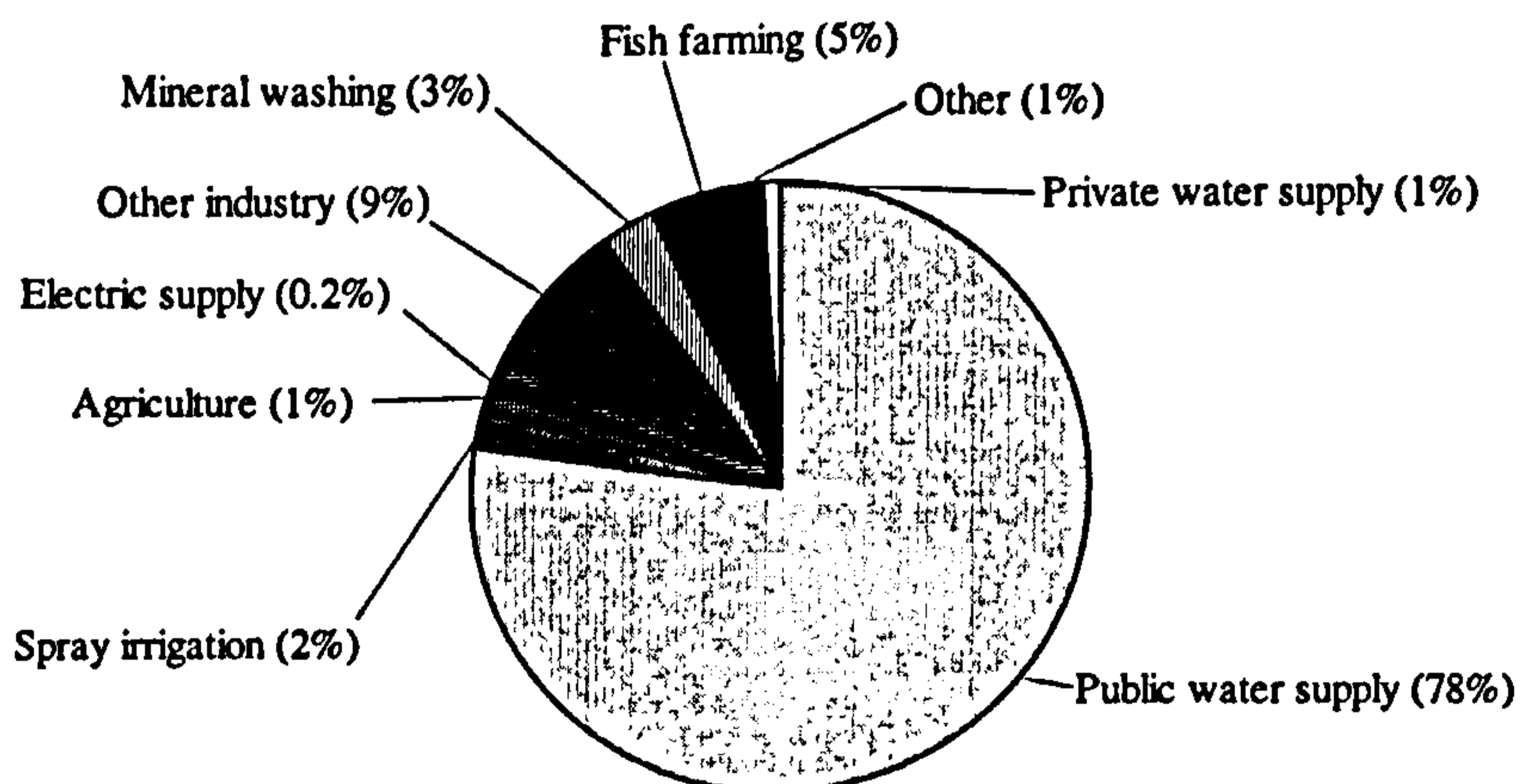


Figure 2.8: Groundwater abstraction as a percentage of total water abstraction (not just for public supply) for some countries in Europe and North America (Source: Economic Commission for Europe, 1992: p48; Eurostat Statistical Office of the European Communities, 1995: p18)

Focusing on England and Wales (Table 2.2) the data show that approximately 30% of all water abstracted for drinking water is groundwater. However, that quantity of groundwater represents approximately 75% of all groundwater abstracted in England and Wales (the exact percentage varies slightly from year to year) making drinking water the most common use for groundwater (Figure 2.9). Harris (1997) states that groundwater currently forms approximately 35% of drinking water supply.

**Table 2.2:** Groundwater abstracted in England and Wales as a percentage of total abstractions for drinking water and as a percentage of groundwater used for drinking water (Department of the Environment, 1994c: p58-62; Department of the Environment, 1996a: p75-78)

Year	Total abstractions for public water supply (MI/day)	Total groundwater abstractions for public water supply (MI/day)	Total groundwater abstractions for all uses (MI/day)	Groundwater abstractions as % of total public water supply	Groundwater abstractions for public water supply as % of total groundwater abstractions
1985	16,695	5,303	6,907	31.8	76.8
1990	18,336	5,519	7,421	30.1	74.4
1994	16,735	5,261	6,777	31.4	77.6



**Figure 2.9:** Estimated abstractions from groundwater by purpose for 1994 for England and Wales (Department of the Environment, 1996a: p78)

Groundwater is considered a superior source of drinking water due to its often high quality, for example, it is much less likely to contain pathogenic organisms than surface water (Price, 1996: p200). The amount of groundwater used for drinking water varies from region to region in England and Wales: for example, in the Southern region, 77% of drinking water supply comes from groundwater but in Wales this figure falls to only 6% (NRA, 1995a: p4). This variation in supply is repeated in other countries, e.g. in the USA, California uses significantly more groundwater than any other state (Price, 1996: p208) and in Canada, Prince Edward Island is



100% reliant on groundwater, while in the Northwest Territories it forms only 1% of public supply (Environment Canada, 1990).

Although groundwater is clearly an important resource for drinking water supply, it is also utilised by industry, agriculture and others (Figure 2.9). What is not demonstrated by these data is the essential role of groundwater in supplying the base flow of rivers, streams and springs (Environment Agency, 1998: p6). This is a clear environmental role of groundwater that has become increasingly apparent in recent times due to the publicity that reduced flow in rivers and the drying-up of springs that can occur (because of over-abstraction of groundwater) during dry weather periods (Lerner, 1997). Groundwater can form a substantial part of river flow in dry weather and is often essential to maintaining that flow (Harris, 1994) this role is not restricted to England and Wales and has been recognised elsewhere (e.g. Environment Canada, 1990). However, in many areas of the world this role of groundwater is not yet fully recognised (Stanners & Bordeau, 1995: p65).

Although care should be taken when interpreting data from different countries as many classify abstractions slightly differently, the importance of groundwater as a water resource both to humans and the environment can be clearly demonstrated and its subsequent protection should take a high priority. Some research has identified the economic benefits of such groundwater protection (e.g. Raucher, 1983; Massmann & Freeze, 1987) and the costs of groundwater remediation (e.g. Sharefkin, Shechter & Kneese, 1984) support the case of prevention over remediation.

Perhaps the major reasons for the protection of groundwater include (Harris & Skinner, 1992a; Roux, 1995):

- (a) aquifers act as natural low cost storage systems for potable water which require little or no treatment before use, so are valuable in terms of drinking water supply;
- (b) once polluted, groundwater is difficult and sometimes impossible to remediate; and
- (c) once polluted, groundwater remediation is often expensive.

Pollution prevention is preferable to clean-up and it is by using a risk-based approach to groundwater protection and management that such issues can be integrated fully into the regulatory decision-making process. Sometimes clean-up and full remediation of groundwater is considered impossible on technical grounds, for example, in the case of the Coventry groundwater investigations, serious contamination with chlorinated solvents had occurred and clean-up was not considered an option due to "hydrogeological constraints ... and a lack of operational techniques for clean-up" (Lerner *et al.*, 1993). If clean-up is possible it can be financially expensive and take a considerable time e.g., at a Superfund site in California, hydrocarbons had seriously contaminated soil and groundwater. The clean-up operation took

seven years and cost US\$22 million (Smedes, Spycher & Allen, 1993). Although there are a variety of techniques that have been developed for groundwater remediation such as 'pump and treat', 'air-sparging' (Reddy, Kosgi & Zhou, 1995) 'soil vapour extraction' or 'bio-venting', it is extremely difficult to clean-up to drinking water standards (Anon, 1994b). Bioremediation of certain contaminants (especially petroleum hydrocarbons) is now well documented (e.g. Chappelle, 1995; Martin & Bardos, 1996; Norris *et al.*, 1994) although may still be seen "as the do nothing" strategy, attractive to industry (Anon, 1996a).

In England and Wales the Environment Agency has the primary statutory responsibility for groundwater protection. This regulatory basis for groundwater protection and the control of groundwater pollution is discussed in Chapter 4, section 4.2.

### 2.2.3 Sources of Groundwater Pollution

The sources of groundwater pollution are many and varied and the types of substance that are often found to contaminate groundwater include heavy metals (Mikkelsen *et al.*, 1994), chlorinated solvents (Lerner *et al.*, 1993), hydrocarbons (such as petroleum Clark, 1995) pesticides (Kastenberg & Yeh, 1993), nitrate (Lee, Dahab & Bogardi, 1992) and chlorides (from mining wastes - Harris & Skinner, 1992b). Such pollution is found in many areas of the world and can have disastrous effects on the environment and human health. For example, a pesticide factory in Calcutta contaminated the local groundwater with arsenic over a period of 20 years but only in 1989 were symptoms of arsenic toxicity noted in people living near the factory and drinking the contaminated groundwater. Some people died and many more were hospitalised (Chatterjee, Das & Chakraborti, 1993). There is often a lack of awareness that groundwater is being contaminated or that contamination may cause a problem to human health or the environment, and little may be known about potential sources of groundwater pollution (Custodio, 1992; Zoller, 1993). In some countries the problem of groundwater contamination and particularly the human health aspect has been recognised: for example, in the USA, this has been a concern since the mid-1970's and a sophisticated regulatory system has developed to control it (Finley, Lau & Paustenbach, 1992).

The sources of groundwater pollution can be categorised into '*point-sources*' e.g., a leak of trichloroethylene (TCE) used in a dry cleaning operation (Rivett, Lerner & Lloyd, 1990) and '*diffuse sources*' e.g., nitrate leaching from agricultural land (Harris & Skinner, 1992b). Sources (diffuse or point) do not necessarily only release one type of contaminant, for example a landfill site may contain a large range of potential contaminants, unevenly distributed (Kjeldsen, 1993). Groundwater contamination incidents even from a point-source such as a leaking tank or a spill are difficult to characterise in terms of volume, location and timing of the release (Williams & Higgo, 1994). Table 2.3 shows some potential sources of groundwater pollution (point and diffuse) based on a USEPA categorisation.

**Table 2.3: A USEPA classification of groundwater contamination sources (Reichard *et al.*, 1990: p12)**

<b>CATEGORY OF SOURCE</b>	<b>TYPE OF SOURCE</b>
<b>Category I - Sources designed to discharge substances</b>	<b>Subsurface percolation</b> (e.g. septic tanks) <b>Injection wells</b> - hazardous waste, non-hazardous waste (e.g. brine disposal and drainage), non-waste (e.g. enhanced recovery, artificial recharge) <b>Land application</b> - waste water and by-products(e.g. spray irrigation & sludge, hazardous waste, non-hazardous waste)
<b>Category II - Sources designed to store, treat, and/or dispose of substances; discharge through unplanned release</b>	<b>Landfills</b> - industrial hazardous & non-hazardous waste, municipal sanitary waste <b>Open dumps, including illegal dumping</b> (waste) <b>Residential (or local) disposal</b> (waste) <b>Surface impoundments</b> - hazardous, non-hazardous waste <b>Waste tailings</b> <b>Waste piles</b> - hazardous waste, non-hazardous waste <b>Materials stockpiles</b> (non-waste) <b>Graveyards</b> <b>Animal burial</b> <b>Above ground storage tanks</b> - hazardous waste, non-hazardous waste, non-waste <b>Underground storage tanks</b> - hazardous waste, non-hazardous waste, non-waste <b>Containers</b> - hazardous waste, non-hazardous waste, non-waste <b>Open burning and detonation sites</b> <b>Radioactive disposal sites</b>
<b>Category III - Sources designed to retain substances during transport or transmission</b>	<b>Pipelines</b> - transfer of hazardous and non-hazardous waste, non-waste materials <b>Transport</b> - of hazardous and non-hazardous waste, non-waste materials
<b>Category IV - Sources discharging substances as consequence of other planned activities</b>	<b>Irrigation practices</b> (e.g. return flow) <b>Pesticide applications</b> <b>Fertiliser applications</b> <b>Animal feeding operations</b> <b>De-icing salts applications</b> <b>Urban run-off</b> <b>Percolation of atmospheric pollutants</b> <b>Mining and mine drainage</b> - surface mine-related, underground mine-related
<b>Category V - Sources providing conduit or including discharge through altered flow patterns</b>	<b>Production wells</b> - oil and gas wells, geothermal and heat recovery wells, water supply wells <b>Other wells (non-waste)</b> - monitoring wells, exploration wells <b>Construction excavation</b>
<b>Category VI - Naturally occurring sources whose discharge is created and/or exacerbated by human activity</b>	<b>Groundwater-surface interactions</b> <b>Natural leaching</b> <b>Salt-water intrusion/brackish water upconing</b> (or intrusion of other poor-quality natural water)

A 1988 report prepared for the Department of the Environment entitled 'The Assessment of Groundwater Quality in England and Wales' (Sir William Halcrow and Partners Ltd, 1988: p37) identified several activities as 'threats to groundwater quality'. These were agricultural activities (nitrates and pesticides); landfills; transport, handling, storage and disposal of compounds used by industry (particularly organic compounds); mining activities and acidification (due to acid rain infiltration). This report was the first to consider groundwater quality on a national basis for England and Wales and concluded that point and diffuse sources

of pollution were a threat to the groundwater resource. Although groundwater quality at that time was considered good, it was recognised that the 'problems associated with contamination' were increasing.

Recently, the European Environment Agency has, as part of a European wide assessment of the environment (Europe's Environment - The Dobriř Assessment, Stanners & Bordeau, 1995: p67), attempted to identify the most common groundwater pollutants in Europe, they are listed as :

- Point sources such as those associated with industry, the urban environment, mining, military and landfill areas
- Leaching of nitrates
- Leaching of pesticides
- Acidification

This report does conclude that data on polluted groundwater sites in Europe, as a whole, are scarce but is broadly in line with the 1988 assessment of groundwater quality of England and Wales (Sir William Halcrow and Partners Ltd, 1988).

In the past, attention (both regulatory and research) has often been focused on landfill operations. For example Aldrick, Edworthy and Young (1986) stated that "The principal potential source of pollution to (ground) water resources arises from the landfill disposal of wastes". A survey carried out in 1995 on the impact of old landfills on groundwater quality in England, found that although groundwater had been affected at approximately 70% of sites investigated, 20% of these sites were 'putting public supplies at risk' but only 3% of sites had actually affected public supplies (Anon, 1997a). In recent years other potential point-sources (e.g., chlorinated solvents) have been acknowledged as also having an impact on groundwater in the UK (Lerner *et al.*, 1993).

The Environment Agency (for England and Wales) has recently published a report entitled 'Groundwater Pollution - Evaluation of the Extent and Character of Groundwater Pollution From Point Sources in England and Wales' (de Hénaut *et al.*, 1997). This work was intended to follow on from the 1988 assessment of groundwater quality (Sir William Halcrow and Partners Ltd, 1988) but with a focus on point-sources of groundwater pollution. A survey was carried out of Agency officers involved in groundwater protection and details of sites with a known or potential impact on groundwater were recorded from them. This survey of point-source groundwater pollution is acknowledged to be limited (Harris, 1997) but to date is the most comprehensive to have been undertaken in the UK (de Hénaut *et al.*, 1997: p13; Anon, 1996b). The survey methodology and the results obtained are described below.

Point-sources were categorised into a series of land-use categories as follows:

- Chemicals (pharmaceuticals, wood treatment plants, paint works)
- Petrochemicals (oil refineries, fuel storage depots)
- Metals (iron and steel works, smelters, electroplating/anodising/galvanising works)
- Energy (gasworks, power stations)
- Transport (garages, maintenance shops, railway depots/sidings)
- Waste Disposal (landfill sites)
- Water Supply and Sewage Treatment (septic tanks, sewage treatment plants)
- Agriculture (leaking silage clamps, pesticide preparation)
- Residential (fuel oil spills, leaking oil tanks)
- Retail (retail parks, fuel oil spills)
- Military (Ministry of Defence sites e.g. military air bases)
- Petrol Service Stations (spillages, leaking underground storage tanks)
- Light Industrial (light industrial warehouses, premises)
- Pits and Quarries (sand and gravel extraction, quarrying)
- Mines and Spoil Heaps (abandoned mines and associated spoil heaps)
- Miscellaneous (docks, wharves, quays, sites not falling into any other category)

At each site the contaminants identified were also categorised, into:

- Metals
- Solvents
- Hydrocarbons
- Pesticides
- Phenols
- Organic (other)
- Inorganic (other)
- Sewage
- Landfill Leachate
- Silage
- Radioactivity
- Miscellaneous Industrial

Based on these categorisations, 1205 point-sources were identified for England and Wales. Of these, 210 (17%) had actually impacted on an abstraction point but 777 (64%) had caused known groundwater pollution. Of the total number of point-sources, 56% were underlain by major aquifers, 39% by minor aquifers and 4% by non-aquifers, although the data is acknowledged to be biased towards the more vulnerable areas (de Hénaut *et al.*, 1997).

Overall the land-use category causing most of the pollution was 'Waste Disposal' although this was felt to be because landfill is highly regulated and monitored and therefore there is greater awareness of this land-use amongst Agency officers. Other land-use categories causing pollution varied from region to region but those most frequently identified included Chemicals, Metals, Energy and Petrol Service Station categories. At sites where groundwater contamination had been confirmed, hydrocarbons, solvents and metals were the most frequently

identified contaminant categories. The most common hydrocarbons were diesel, petrol and fuel oil. The relative importance of hydrocarbons and petrol-filling stations as point-sources of groundwater pollution was one of the reasons for focusing this research on such issues.

Using this information on land-use and contaminants, sites were then subjectively assessed on the basis of 'point-source severity' in relation to 'risk of pollution to groundwater' in order to provide a prioritisation of sites at a national level. An assessment scale of 1 to 5 was used; 1 representing gross contamination of a major aquifer and 5, slight contamination of a minor or non-aquifer. Examples of these categories are shown in Table 2.4.

**Table 2.4:** Environment Agency point-source severity categories with example sites (de Hénaut *et al.*, 1997: p10-12)

Rating	Point-Source Severity Category	Example sites
1	<i>High Significance</i>	Dry cleaning facility on a major aquifer, in source protection zone 1, solvent contamination of borehole
2	<i>Medium-High Significance</i>	Engineering works (tank cleaning) on a major aquifer, hydrocarbons, PCBs and solvent contamination, groundwater is contaminated but no affected boreholes identified
3	<i>Medium Significance</i>	Petrol-filling station on a non-aquifer overlying a major aquifer, in source protection zone 2, hydrocarbon contamination of groundwater, no impacted boreholes identified
4	<i>Medium-Low Significance</i>	Gasworks on a non aquifer, mineral oil, PAHs and cyanide contamination, groundwater contaminated but no impacted boreholes, surface water known to be affected
5	<i>Low Significance</i>	Landfill site on a non-aquifer, leachate contamination (ammonia) of groundwater, no impacted boreholes identified, surface water known to be affected

In order to classify a site on the basis of 'point-source severity', several pieces of information or factors were utilised. These were:

- Point-source - type of source e.g. dry cleaning works
- Land-use/Activity - more detailed background on what had happened at the site
- Nature of the Contamination - what contaminants had been identified
- Extent of the Contamination - monitoring carried out, levels of contaminants
- Date of Pollution - when pollution was first discovered (and how)
- Hydrogeology - brief details on site hydrogeology, aquifer type, source protection zone etc.
- Remediation - what investigations and remediation work had been carried out or was proposed at the site

These factors were used subjectively, for example, no attempt was made to 'score' answers. The 1205 point-sources identified were classified as follows:

High significance	8%
Medium High significance	17%
Medium significance	28%
Medium Low significance	32%
Low significance	15%

The most common contaminants or suspected contaminants were identified as metals, landfill leachates and hydrocarbons and these were associated with Medium and Medium-low significance point-sources. Solvent contamination was however, more likely to be associated with High, Medium-high or Medium significance point-sources (de Hénaut *et al.*, 1997: p8). In terms of hydrocarbon contamination this is discussed further in the next chapter, Table 2.5, however demonstrates how a hydrocarbon point-source could vary in terms of risk to groundwater. Full characterisation of the source term is an important part of any categorisation or assessment process.

**Table 2.5:** Variability in some example hydrocarbon point-sources in terms of physical hazards, control procedures and overall risk to groundwater

Source	Risk elements		Overall risk to groundwater
	<i>Physical hazards e.g. type of product, volume</i>	<i>Control Procedures - level of site management</i>	
Crude oil refinery	High	High	High
Bulk petroleum storage facility	Medium-High	Medium-High	Medium-High
Retail petrol-filling station	Medium	Medium	Medium
Vehicle maintenance depot	Medium-Low	Medium-Low	Medium-Low
Residential fuel/oil tanks	Low	Low	Low

The Agency survey of point-sources of groundwater pollution in England and Wales recognised that there is a wide variation in types of source of pollution in terms of land-use and type of contaminant, with hydrocarbons, solvents and metals the most common groundwater contaminants in England and Wales.

## CHAPTER 3

### 3 HYDROCARBONS AND GROUNDWATER POLLUTION

#### 3.1 INTRODUCTION

Hydrocarbons as a group of substances exhibit a wide variety of characteristics. However, many of the hydrocarbons likely to contaminate groundwater are relatively insoluble in water and are termed non-aqueous phase liquids or NAPLs. These substances are further divided into dense NAPLs or DNAPLs (denser than water) and light NAPLs or LNAPLs (lighter than water) (Price, 1996: p253).

The term 'petroleum hydrocarbons' covers a wide variety of substances that may impact on groundwater and includes materials such as petrol and diesel fuel. These hydrocarbons have specific properties that can influence the behaviour of these materials once released into the environment.

#### 3.2 PETROLEUM HYDROCARBONS

Hydrocarbons contain hydrogen and carbon. When combusted, the C-H bonds are broken to form H-O and C-O bonds, and energy is released. It is this energy that is utilised by man. Each product such as 'petrol' is a mixture of many different hydrocarbons obtained from the refining of crude oil. In a typical petroleum 'blend' there may be about a hundred different compounds (Cole, 1994: p40).

The composition of petroleum is a complex mixture of hydrocarbons including alkanes, cycloalkanes, alkenes and aromatic hydrocarbons such as benzene. Table 3.1 lists some of the more important components of petroleum and some other common petroleum hydrocarbons such as diesel.

The solubility in water of these petroleum hydrocarbons is relatively low (they are LNAPLs), but petroleum as a whole is made up of a range of substances with varying solubilities. Benzene, toluene, ethylbenzene and the xylenes are commonly referred to as the BTEX compounds and represent the most water-soluble fractions of a fuel. If there has been a spill or a leak into the ground, these compounds will often be found at the head of any subsequent contaminant plume. It is for this reason that the BTEX compounds can be used to determine what has been released and to some degree the extent of the plume (Cole, 1994: p120).



**Table 3.1:** Volatility and solubility in water of some petroleum products (Cole, 1994: p62)

Product	Flash point (°C)	Solubility in cold water at 20°C (ppm)
Petrol	-30 to -43	50 to 100
1-Pentene		150
Benzene	-11	1,791
Toluene	4	515
Ethylbenzene	18	75
Xylene	27	150
n-Hexane	-40	12
Cyclohexane		210
i-Octane		8 ppb
Kerosene	40 to 75	<1
Diesel	40 to 65	<1
Light Fuel Oil	40 to 100	<1
Heavy Fuel Oil	65 to 130	<1
Lubricating Oil	150 to 225	<1 ppb

### 3.2.1 Degradation and Migration of Petroleum Hydrocarbons Once Released

The environmental effects of the use of petroleum as a fuel are not restricted to groundwater pollution and can be divided into two broad categories:

- (i) atmospheric effects - release of CO<sub>2</sub>, SO<sub>x</sub> and NO<sub>x</sub> due to combustion, release of petroleum products due to spills/leaks (volatilisation), and
- (ii) contamination of groundwater, surface water and soil - release of petroleum due to spills/leaks

Both these categories of exposure can have impacts on human health as well as the environment as a whole. The number of potential pollution sources is enormous, the use of petrol and diesel as a fuel is a ubiquitous part of an industrialised culture. It is hydrocarbon pollution due to the second route of exposure, groundwater pollution via spills and/or leaks, that was the focus of this research, particularly the effect on groundwater from point-sources of pollution such as petrol-filling stations.

Once a release has occurred and hydrocarbons have entered the ground, the location of the spill or leak becomes important. The physical characteristics of the surface and sub-surface can impact on the behaviour of the fuel that has been released. The porosity (void space) the permeability (ability to transmit liquids) and the particle size of the subsurface are all key to the way a petroleum hydrocarbon release will behave (Cole, 1994: p76).

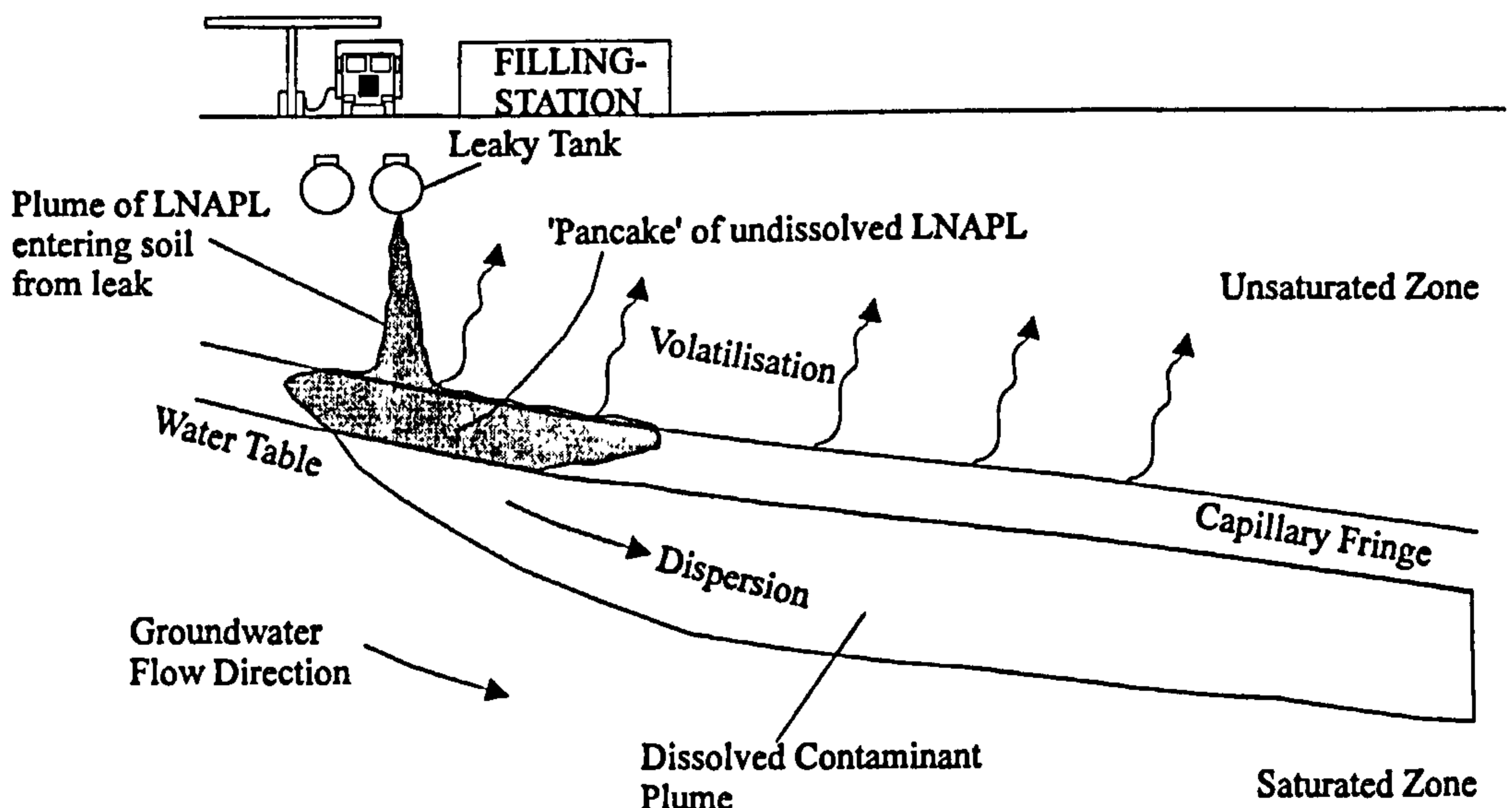
Due to the low solubility of petroleum hydrocarbons (LNAPLs) on release into the subsurface they can be found in several forms (or phases):

- Vapour phase

- Free phase product (bulk liquid phase)
- Adsorbed phase
- Dissolved phase

When a LNAPL enters the soil or unsaturated zone it will enter the pore spaces as free-phase product and displace the air, a process of dispersion that takes place more readily in a sand or gravel media as opposed to clay. Some of the hydrocarbon may enter the vapour phase (volatilisation) and enter pore spaces not already occupied by water or free phase product. If the source of the release is large enough, downward movement will continue until reaching the capillary fringe. At this point a LNAPL will flow along the capillary fringe and may even depress the capillary fringe to spread along the water table to form a 'pancake' (Figure 3.1) (Price, 1996: p255).

Although solubility of the petroleum hydrocarbons is relatively low, it is not zero. Therefore, as the water table falls and rises the LNAPL is distributed into the aquifer, as some product will dissolve into the groundwater and will move with the groundwater flow to form a plume of contamination. The rate of this movement depends on the rate of (i) groundwater flow, (ii) adsorption of the hydrocarbon on to soil particles, (iii) biodegradation by micro-organisms, and (iv) volatilisation (movement of dissolved phase product into the gaseous phase in the unsaturated zone) (Cole, 1994: p80). A schematic diagram of groundwater contamination by a LNAPL such as petroleum is shown in Figure 3.1.



Adsorption will also occur in the fluctuation zone where the water table rises and falls  
 Biodegradation will also take place if there is sufficient oxygen, nutrients and micro-organisms

Figure 3.1: LNAPL penetration into an aquifer (Cole, 1994: p89; Environment Agency, 1996b: p14; Price, 1996: p254)

The rate of adsorption onto soil particles is also termed retardation and can be expressed as a fraction of groundwater flow or velocity: the 'retardation factor'. This factor is dependent on the soil type and the individual compound under investigation, e.g. benzene or MTBE (a fuel additive). Calculation of the retardation factor can give an approximate estimate of how far dissolved phase hydrocarbon could migrate per day and hence an estimate of how long it will take to reach a potential target (as long as the location of the target is known) (Freeze & Cherry, 1979: p404; Environment Agency, 1996b: p15).

Hydrocarbon contaminants do not only form (or partition) into one phase, but often into several. For example, benzene is expected to partition as 5% adsorbed onto soil particles, 60% in the vapour phase and 35% in the dissolved phase (Cole, 1994: p84). This can have implications for remediation: for example, using vapour extraction and pump and treat systems will initially decrease the amount of benzene (detected by BTEX analyses), but if the treatment continues for a long period of time (long enough for the water table to rise and fall) benzene levels will rise again as the adsorbed portion of benzene is flushed out (Cole, 1994: p82).

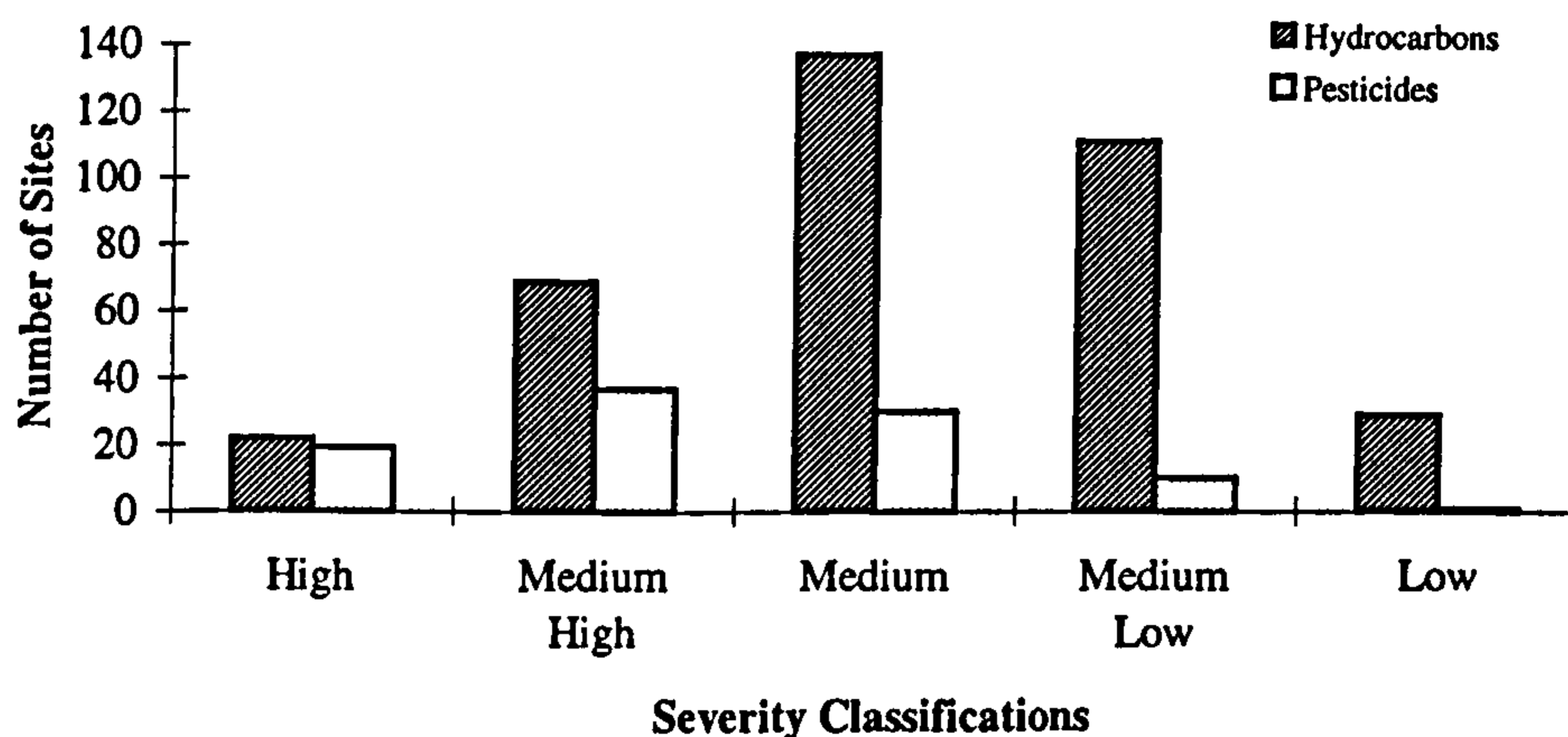
Although information such as transport times calculated from retardation factors and actual chemical analyses of groundwater samples can be extremely useful, care must be taken to ensure that what is actually happening is clear. This takes experience and expertise on the part of the person investigating the petroleum release and it is possible to make quite large errors of judgement.

Pollution of groundwater by DNAPLs such as chlorinated solvents is common in urban industrial areas in the UK: for example, the Coventry, Birmingham, Luton and Dunstable areas have been studied in detail (Longstaff *et al.*, 1992; Lerner *et al.*, 1993; Nazari *et al.*, 1993). LNAPLs such as petroleum hydrocarbons have also been responsible for several groundwater pollution incidents in the UK, particularly from underground storage tanks (Harris, 1993). Urban run-off can also be source of petroleum hydrocarbon groundwater pollution (Price, 1994). These types of incidents are of course not restricted to the UK and occur in other industrialised countries, e.g. France (Roux, 1995).

The recent Environment Agency report on groundwater contamination point-sources (de Hénaut *et al.*, 1997) confirmed that hydrocarbons such as petroleum are a significant source of groundwater pollution in the UK. Focusing on the contaminant group 'hydrocarbons', Figure 3.2 compares the distribution of sites contaminated with hydrocarbons across the five point-source severity categories ('pesticides' are shown for comparison).

Of the hydrocarbon contaminant group, diesel and petrol were the two most commonly identified pollutants, and sites where hydrocarbon contamination had been identified, were most often classified as being of medium or medium-low significance in terms of point-source

severity. This may be mis-leading in terms of the numbers of sites identified as causing point-source hydrocarbon pollution. A total of approximately 350 sites were classified as being contaminated with hydrocarbons (suspected and confirmed contamination) compared to approximately 100 sites contaminated with pesticides (Figure 3.2). Each individual hydrocarbon contaminated (or potentially contaminated) site may be rated medium or medium-low significance in terms of 'risk of pollution to groundwater' but there are potentially more sites to present a problem.



**Figure 3.2:** Hydrocarbon and pesticide contamination and subsequent point-source site severity classifications (de Hénaut *et al.*, 1997: p9)

As a source of petroleum hydrocarbons, petrol-filling stations have polluted underlying aquifers and impacted on drinking water boreholes in the UK (Anon, 1994c) and Shell UK was the first petrol-retailer to be prosecuted for polluting groundwater with petrol (under the Water Resources Act) in 1995 (Anon, 1995a and 1995b).

The impact of petroleum hydrocarbons on groundwater has also been recognised outside of the UK. For example, the United States Environmental Protection Agency administers a range of 'Underground Storage Tank' (UST) regulations specifically aimed at controlling petroleum USTs by preventing, detecting and correcting problems caused by spills and leaks of petroleum fuels (USEPA, 1988).

### 3.3 PETROL-FILLING STATIONS AS POINT-SOURCES OF GROUNDWATER POLLUTION

Petroleum hydrocarbons such as petrol and diesel present a particular problem to the groundwater environment, mainly due to the large number of potential sources, the way the product is stored and distributed and the addition of compounds such as MTBE to the product.

Several petroleum fuels are marketed in the UK, all with slightly different compositions. Table 3.2 shows the acceptable range of the major components of unleaded petroleum as sold in the European Community.

**Table 3.2:** Composition of unleaded petroleum fuel (Commission of the European Communities, 1996)

Component	Composition (%)		
	Max	Min	Av.
Alkanes (saturates)	43	63	53
Alkenes (olefins)	14	8	11
Aromatics	41	29	35
Benzene*	2	-	2
Boiling pt (°C)	>27	>25	-

\* Included in figure for aromatics (%)

Although many of the characteristics of the various fuel types do not produce a significant change in their behaviour in terms of pollution of groundwater, there are some key differences between fuels that can affect their potential impact on groundwater. The most important are:

- the difference in solubility/viscosity of diesel compared to petrol
- type of additives found in unleaded and leaded petrol and their proportions

Diesel fuel is much less soluble than petrol in water (< 1ppm as opposed to 50-100 ppm). It also has a higher viscosity than petrol, allowing petrol to move through the soil/rock matrix faster than diesel. Diesel, if released into the soil will migrate but at a slower rate than petrol (Cole, 1994: p66).

In terms of carcinogenic risk to humans, the amount of benzene and PAHs contained in a fuel are key factors. The risk associated with petroleum is greater than that for diesel, as benzene concentrations are higher in petrol but PAH concentrations are comparable in the two fuels (Morgan & Swett, 1994).

Fuels such as leaded and unleaded petroleum often contain additives as part of the blend. Leaded petrol contains tetraethyl lead as an octane booster but unleaded fuels are likely to contain an octane boosting additive (an oxygenate) such as methyl-tertiary-butyl-ether (MTBE) (Cole, 1994: p73). A variety of oxygenates are used by different companies in various countries, exact fuel compositions are problematic to state categorically. Modern fuels are not only likely to contain octane enhancers, they may also contain detergents, anti-oxidants, anti-icing additives and anti-corrosion additives.

Currently, however, it is the addition of oxygenates to fuels that is causing concern in the UK (Anon, 1993a; Lowe, 1995; Turrell *et al.*, 1996) and elsewhere e.g., the USA (Squillance, 1995). In the UK, the maximum amount of MTBE added to a fuel is approximately 10% but is

usually much lower (1-2% Lowe, 1995: p4) and some companies such as Shell do not use MTBE at all in the UK (Turrell *et al.*, 1996: p16). MTBE can be added to leaded as well as unleaded fuel and in 1994 was found in approximately 40% of all UK petrol (Lowe, 1995: p18). MTBE is more soluble than the other components of petrol (BTEX compounds for example) and therefore if it is present in a product and a release occurs, it will be expected to occupy more of the subsurface and any subsequent contaminant plume and could act as an 'early warning' of a release (Turrell *et al.*, 1996: p76).

Hydrocarbon point-sources of groundwater pollution incorporate areas where hydrocarbons are stored and/or used in underground or above ground tanks, or transported by pipe or by vehicle. These type of sources can include petrol-filling stations, petrol distribution facilities, commercial and agricultural storage facilities, pipelines and tankers used to transport fuel. The petrol-filling station has been the focus of this work but Figure 3.3 shows the whole petroleum distribution cycle, illustrating other areas of potential contamination.

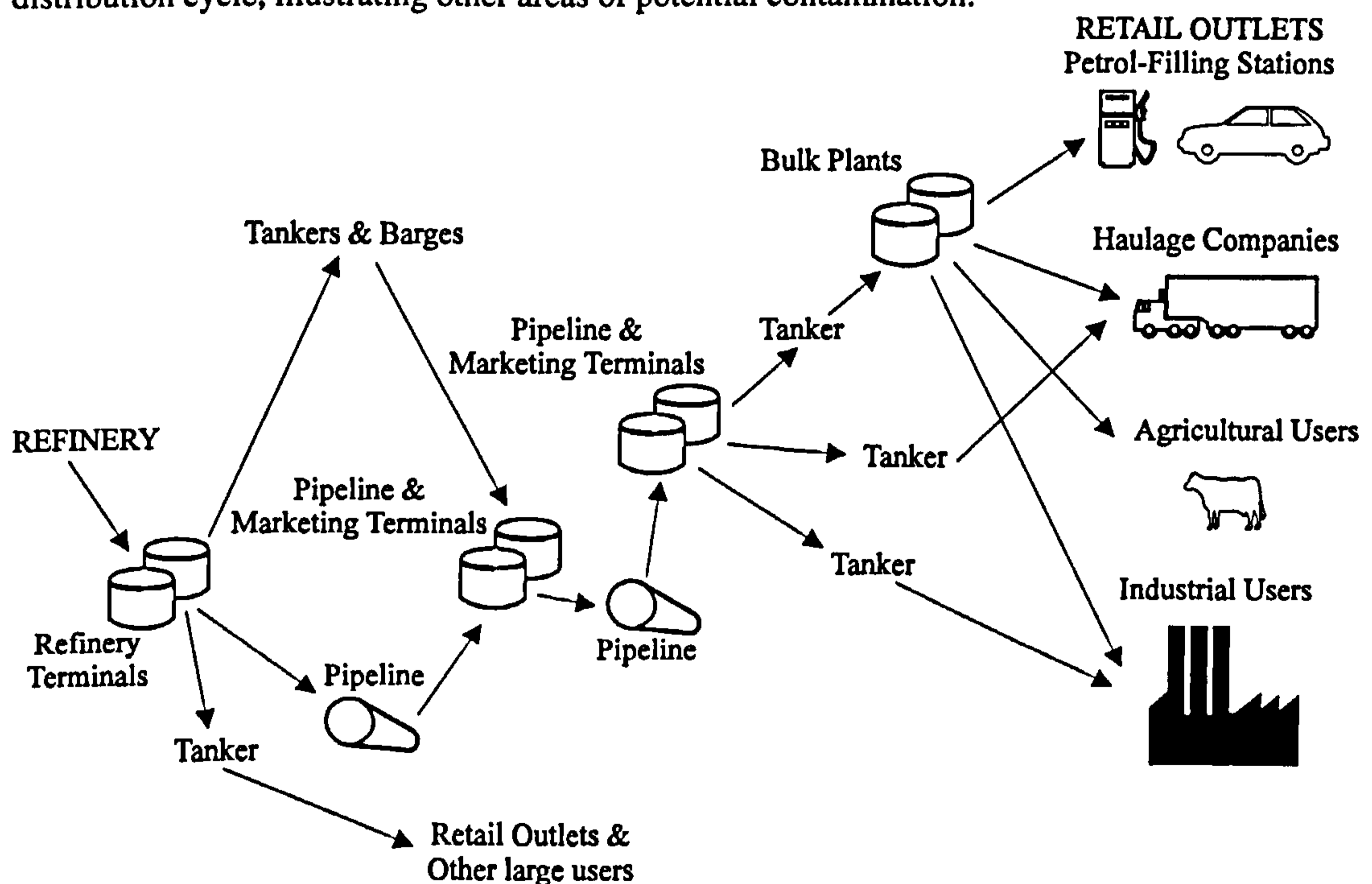


Figure 3.3: The petroleum distribution cycle (Turrell *et al.*, 1996: p26)

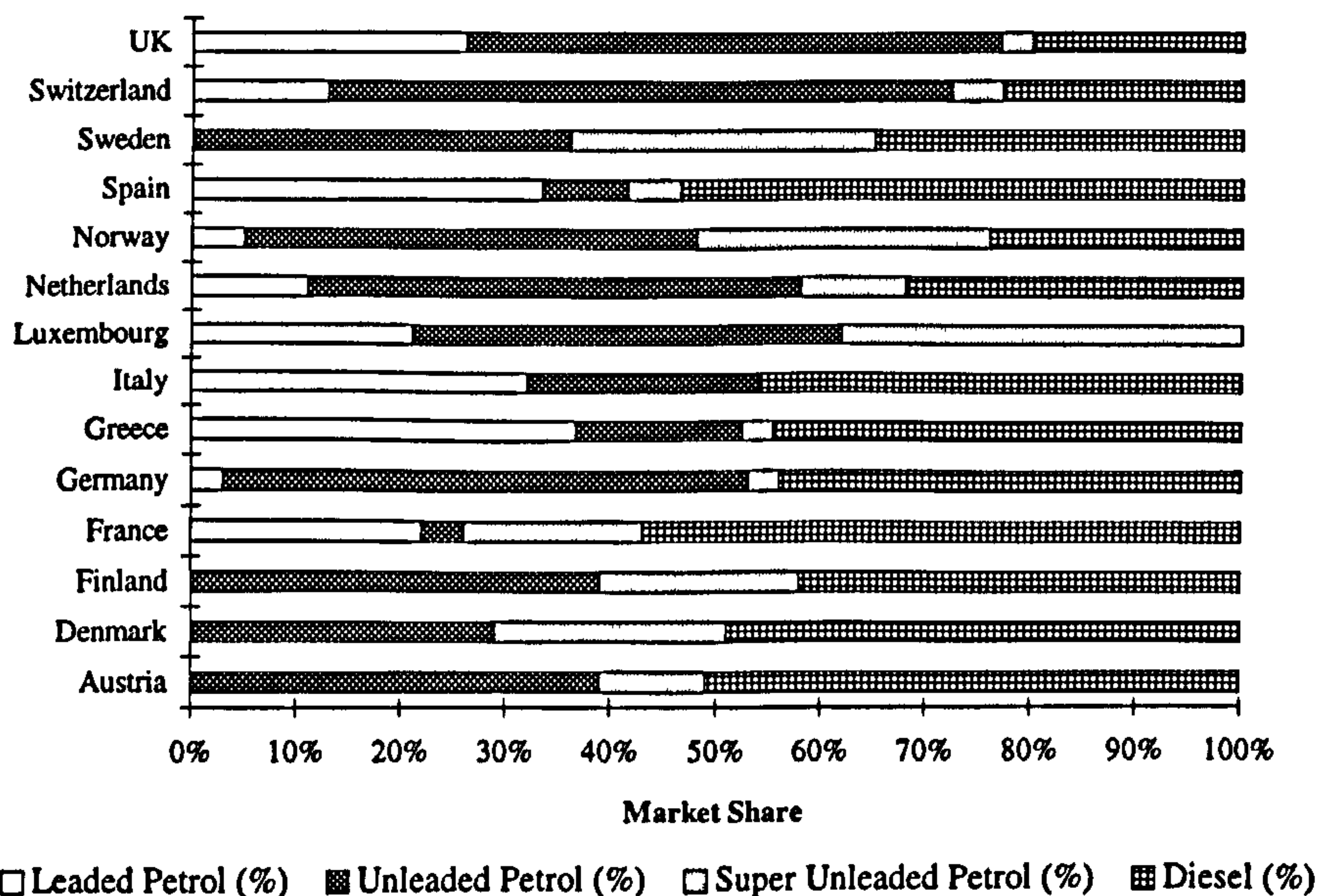
The amount of fuel delivered to customers in the UK in 1996 was estimated to be 36,596,245 tonnes. Of this approximately 75% was delivered to 'retail' customers via petrol-filling stations (IOP, 1997b) and 25% to commercial customers such as freight distribution centres. Table 3.3 shows how this total is formed from the various petroleum products available with a comparison to the 1987 figures. In the UK, the market has changed in recent years with leaded petrol usage falling and unleaded and diesel usage rising in both the commercial and retail sectors.

These changes have not been restricted to the UK and the distribution of leaded and unleaded petrol and diesel sales varies between countries. For example, of total retail fuel sales (including diesel) in Germany, 53% are of unleaded fuel while in Italy the proportion is 22% unleaded (Turrell *et al.*, 1996: p17). Figure 3.4 illustrates the variation in the market share of petroleum fuels across Europe for retail sites i.e., petrol-filling stations (includes diesel sales).

**Table 3.3:** Fuel deliveries to UK petrol-filling stations in 1987 and 1996 for retail and commercial outlets (IOP, 1997b)

Product	Deliveries to Petroleum Outlets (tonnes)		
	1987	1996	Change
<i>Retail Filling Stations</i>			
Leaded petrol (4 Star)	19,519,514	7,059,060	- 63 %
Unleaded petrol	0	14,023,270	+ 100 %
Super unleaded petrol	0	698,185	+ 100 %
DERV	2,094,593	5,547,951	+ 165 %
Retail Sub-Total	21,614,107	27,328,466	+ 26 %
<i>Commercial Outlets</i>			
Leaded petrol	582,160	134,176	- 77 %
Unleaded petrol	0	290,428	+ 100 %
Super unleaded petrol	0	11,134	+ 100 %
DERV	6,374,188	8,832,041	+ 39 %
Commercial Sub-Total	6,956,348	9,267,779	+ 33 %
<b>Overall Total</b>	<b>30,652,629*</b>	<b>36,596,245</b>	<b>+ 19 %</b>

\*Includes 2,082,174 tonnes of 2 & 3 Star petrol



**Figure 3.4:** Market share across Europe for leaded, unleaded and diesel fuels at retail petrol filling-stations (Source: IOP, 1997a: p248)

Figure 3.4 shows that in terms of risk to groundwater from petrol-filling stations in the UK, unleaded petroleum forms approximately 55% of the potential source term, with leaded fuel forming approximately 25%, and diesel forms the remaining 20% (this is for retail sites only,

diesel forms 95% of commercial sales). If a release does occur and the product type is unknown, then it is more likely to be a petrol release (with petrol's associated greater ability to move through the soil/rock matrix) than a diesel release. If the release can be identified as petrol but which type is unknown, it is twice as likely to be unleaded (with the possibility of an MTBE release) as opposed to leaded fuel.

Figure 3.4 illustrates that petroleum sales and therefore site storage rates are not the same in all countries and any assumptions made for a UK risk to groundwater assessment model would not necessarily be applicable elsewhere. This would only be of importance if, for example, the individual products being stored at a site were not known and a 'default option' was used and that was based on the UK situation but the site being assessed was elsewhere.

Another important factor when investigating petrol-filling stations as potential point-sources of groundwater pollution on a national basis, are the actual number of sites present and how much petroleum they handle. Figure 3.5 shows the number of petrol-filling stations in the UK from 1970 to 1996. This graph would imply that petrol-filling stations are presenting a diminishing risk to groundwater in terms of total volume of petroleum that could present a hazard to groundwater, as the number of sites are decreasing. This would be misleading as even though the number of actual sites is decreasing (quite rapidly in recent years) the average throughput of remaining sites is on an increasing trend.

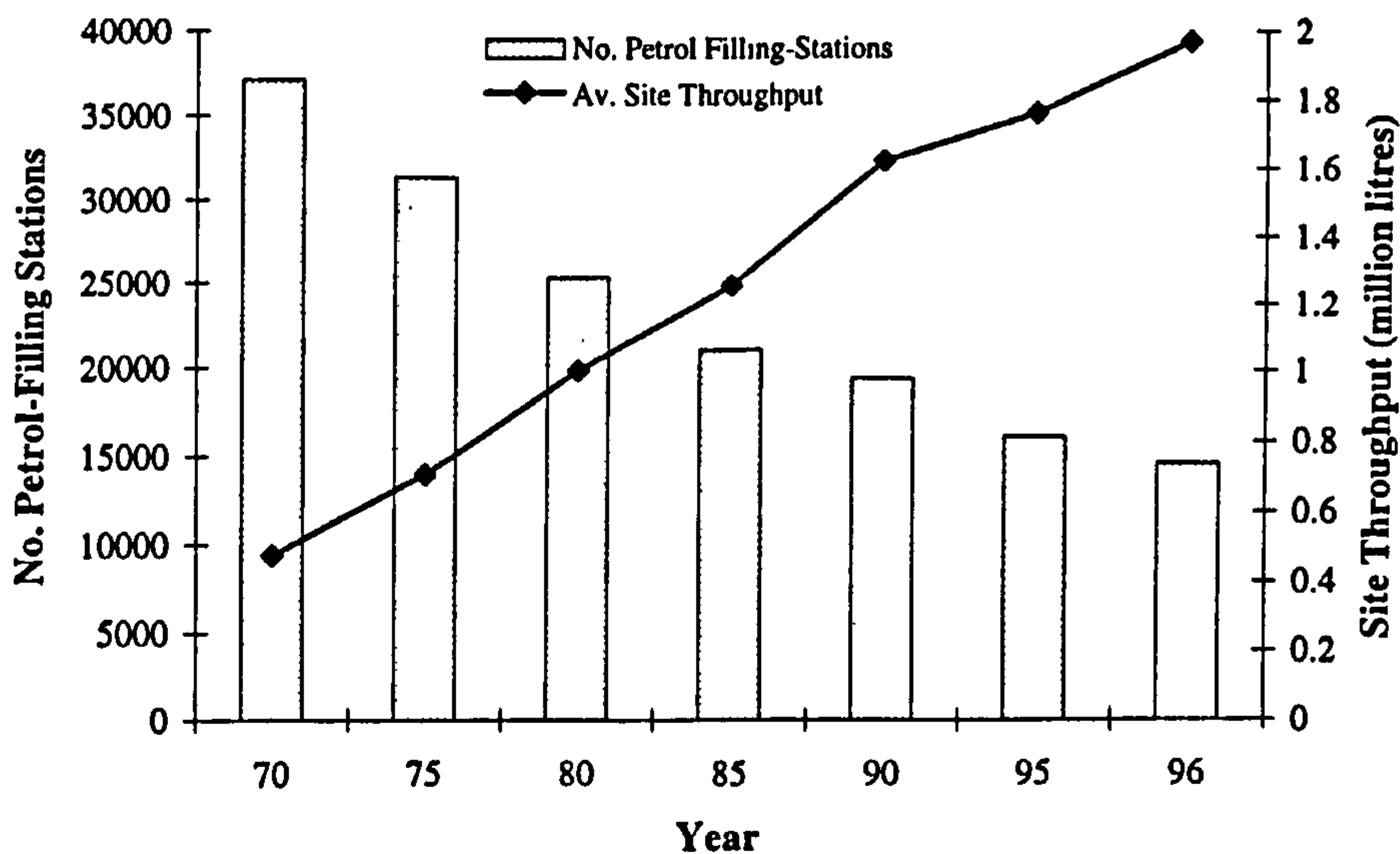


Figure 3.5: Distribution of petrol-filling stations in the UK from 1970 to 1996 and the average site throughput in millions of litres of product (IOP, 1997b)

In 1995, the average throughput for a petrol-filling station was 1.76 million litres of fuel, but there were a significant number of 'supersites' dispensing considerably more. The number of sites in the higher throughput categories (2 million litres and above) is increasing as the



smaller, less economic sites are closed down (Service Station Magazine, 1995). In 1996, the average site throughput was 1.97 million litres, across nearly 15,000 sites, with some sites having a much higher throughput of 5 million litres or more. In terms of risk to groundwater, petrol-filling stations still present both a large-scale and significant point-source pollution risk problem.

Although factors such as product throughput and number of sites are critical when demonstrating the importance of petrol-filling-stations as potential point-sources of groundwater pollution, when considering strategic management options on a national basis, and when assessing an individual site, factors such as site construction and operation become significant.

### **3.3.1 Structure and Operation of a Petrol-Filling Station**

The structure and operation of a petrol-filling station is primarily governed by the fact that petroleum is a hazardous substance. It is a highly flammable liquid and will give off flammable vapours even at low temperatures. It produces a flammable atmosphere at between 1 % and 8% vapour in air. Two Health and Safety Executive Codes of Practice are routinely used in the UK. The first (which is currently being up-dated) governs site construction and operation (HSE, 1990). The second deals with the assessment and control of fire and explosion risk (HSE, 1996b). Although the latter is focused on controlling fire and explosion at petrol-filling stations it can also have positive environmental implications. The Institute of Petroleum also publishes codes of practice governing site design, operation etc. (e.g. IOP, 1993; IOP, 1995). Advice and guidance is also produced by bodies such as the UK Petroleum Industry Association and the American Petroleum Institute.

A typical retail petrol-filling station consists of:

- a) Fuel delivery area where tankers can off-load fuel
- b) Fuel storage tanks and associated pipelines - tanks etc. are usually underground (USTs)
- c) Dispensing areas where fuel is dispensed to the customers vehicle
- d) Retail shop where person controlling the site is situated

Fuel can be released into the environment at the delivery, storage or dispensing stage.

#### *Tank Systems*

In the UK, fuel has traditionally been stored in single skin, mild steel underground tanks although in recent years glass-reinforced plastic (GRP) tanks have become available, as have double skinned steel tanks (Environment Agency, 1996b: p17). GRP is also known as FRP

(fibreglass reinforced plastic). A double-skinned tank is a 'tank within a tank' with a small space between called the interstitial space. This space can be used to fit monitoring equipment which can detect leaks (HSE, 1996b: p55). These type of tanks have obvious advantages in terms of pollution prevention and the Agency does not recommend that single-skinned tanks be used in designated groundwater protection zones (Environment Agency, 1996b: p17). However, this recommendation can only be applied to new or redeveloped sites, as there are still a large number of single-skinned tanks in use.

There are advantages and disadvantages in terms of pollution control to using steel and GRP as tank construction materials, as shown in Table 3.4.

**Table 3.4:** Advantages and disadvantages of steel and GRP as construction materials for underground fuel tanks (Environment Agency, 1996b: p20)

Type of Material	Advantages	Disadvantages
<i>Steel</i>	Resistant to hydrocarbons Impermeable Mechanically tough Resists deformation (ductile)	Corrodes when in contact with soil or groundwater Heavy (makes installation difficult)
<i>GRP</i>	Resistant to hydrocarbons Impermeable Light weight	Will not resist deformation - brittle Easily damaged on installation

Steel and GRP tanks are the usual construction materials in most areas of the world where fuel is stored in underground tanks, steel being the most common. GRP tanks are accepted in the USA more than in Europe and approximately 4% of tanks in the UK are constructed from GRP (Thompson, 1997). In the US, tanks are being used that combine the advantages of steel and GRP, by producing a double-walled tank made of steel with a polyurethane or GRP 'jacket'.

Tanks can also be re-lined to improve their integrity and provide an interstitial space. This involves installing a 'second skin' in the tank whilst still *in situ* and can be more cost effective than replacing a tank, although the tank must be sound to begin with (USEPA OSWER, 1995).

Whatever the tank material it will be affected by what surrounds it below-ground. There are four types of 'tank surround': concrete, gravel, foam and vaults. Concrete was used to surround all tanks and associated pipelines until recently in the UK, and it is part of the recommended installation procedure (HSE, 1990: p18). The reasoning for using concrete is not clear. Although concrete may delay the corrosion process it has disadvantages in that it may transfer stresses from the subsurface to the tank and will crack during installation (Environment Agency, 1996b: p21). The use of concrete to 'protect' tanks has not been repeated outside of the UK (Moreau, 1986) and it is not now recommended as a tank surround (Thompson, 1993).

Gravel must be used to surround GRP tanks and is now recommended for steel tank installations also. Although it provides no barrier to fuel it does not transfer stress to the tank. The tank does have to be protected from heavy vehicles using the site by a concrete slab above the tank. Using a gravel surround also allows tanks to be removed easily if they do fail or the site closes (Environment Agency, 1996b: p21).

Foam tank surrounds and tank vaults are not commonly used in the UK although both systems provide superior protection to groundwater compared with concrete or gravel. In terms of assessing risk to groundwater from UK petrol-filling stations these types of tank surround can be discounted as the vast majority of existing sites use concrete or gravel.

The risk to groundwater from fuel releases from tanks (and pipes) can be reduced in two main ways, by using:

- tank corrosion protection systems
- overflow protection devices

For steel tanks, guidance document HS(G)41 (HSE, 1990: p18) recommends that tanks are coated in bitumen before installation to provide adequate protection against corrosion. This advice is now recognised as being insufficient in many cases (Environment Agency, 1996b: p23). In the USA, which has a much more sophisticated regulatory control system for underground tanks (containing petroleum), there are three ways of satisfying the corrosion protection requirements (USEPA OSWER, 1995: p16) by:

- installing GRP tanks/pipework, or
- installing steel tanks with a 'non-corrodible' jacket, or
- installing steel tanks/pipework with a corrosion resistant coating and cathodic protection

Cathodic protection can be applied to tanks and associated pipework (there are two systems; sacrificial anodes and impressed current) and although required in the USA for steel tanks (even double-walled ones) it is not commonly found in the UK. It is however, recommended by the Environment Agency to be fitted at sites being redeveloped in a groundwater protection zone I (Environment Agency, 1996b: p38).

Overflow protection devices can be mechanical or electronic. Mechanical devices include the ball-float valve that shuts off the flow of fuel into a tank: as the fuel level rises, the ball floating on the surface blocks off the fill pipe. A second device is called an 'automatic shutoff device', which uses a float, again, on the fuel surface that once it reaches a certain position shuts off a valve on the fill pipe. Overflow protection devices are required on all new underground fuel

tanks in the USA and will be required on all tanks by the end of 1998 (USEPA OSWER, 1995: p14). In the UK such devices are required by the Environment Agency for new sites and sites being redeveloped in all groundwater protection zones (Environment Agency, 1996b: p36).

### *Pipework Systems*

Pipework is required to connect the delivery point to the tanks and the tanks to the dispenser pumps. Two systems are used to transfer fuel: 'suction systems' where the fuel is pumped to the dispenser by a pump actually in the dispenser, and pressure systems where the fuel is pumped to the dispenser by a pump in the tank. Pressure systems are considered less safe than suction systems as if a leak develops fuel will continue to flow from the tank even if no fuel reaches the dispenser, as the system is under positive pressure (Environment Agency, 1996b: p24). The majority of sites in the UK use a suction system (Stapleton, 1997).

Delivery points on most sites are usually 'off-set' i.e., the tanker does not pump fuel directly into the tank but connects to a point, usually away from the fuel dispensing area. This off-set fill can be above-ground (where it should be bunded to prevent escape of spills) or below-ground in a chamber that has secondary containment. HS(G)41 (HSE, 1990: p26) recommends that above-ground fills are protected from 'impact' and below-ground fills are contained in a chamber. The Environment Agency (1996b: p28) recommends that off-set fills are located above-ground and fully bunded. Pipes are also required to take fuel from the tank to the pump and on to the customer.

Pipes unlike tanks have to go around corners and therefore require connections and joints. These areas can provide points of weakness and require great care on installation to ensure a sound system. The Institute of Petroleum has produced specific guidance for the installation and testing of underground pipes (IOP, 1995). There are three types of material recommended for use as underground pipes: metal (usually steel), GRP and plastic. Steel and GRP pipes have similar advantages and disadvantages to those of tanks of the same material (Table 3.4). Plastic pipes, although flexible (require less joints), can have an unacceptable permeability ( $> 2\text{g/m}^2/\text{day}$ ) and require lining (Environment Agency, 1996b: p25).

As with tanks, pipes can have secondary containment in the form of double-walls or 'jackets'. In the USA, pipes must be made of GRP or steel with cathodic protection (USEPA OSWER, 1995: p21). In the UK, pipes do not usually have secondary containment although this is recommended by the Environment Agency in all designated groundwater protection zones (combined with interstitial monitoring in groundwater Source Protection Zone I) (Environment Agency, 1996b: p36).

An alternative method of secondary containment for tanks and pipes is the use of flexible membranes instead of double-walls. These systems are being promoted for use in the USA as a more cost-effective way of complying with the regulations (Semonelli, 1990). The membrane system is similar in appearance to a landfill liner system. It can also be used as a kind of barrier system for a petrol station forecourt to prevent any spills penetrating the forecourt and entering the ground. This use is not favoured by the Environment Agency (Environment Agency, 1996b: p29).

### *Leak Detection and Monitoring Systems*

There are a variety of methods that can be used to detect and monitor for leaks, although even the most sophisticated is not fail-safe (USEPA OSWER, 1989). They can be sub-divided as follows:

- tank gauging methods
- interstitial monitoring
- monitoring wells

The most basic method is a form of inventory control where the volume delivered by tanker and the volume dispensed to customers is recorded along with a measurement of the tank contents using a 'manual dip stick'. Any differences are called the wet stock loss/gain. The USEPA differentiates between inventory control when the tanks are dipped daily and 'static tank testing' which is also called manual tank gauging. With static tank testing the tanks are dipped at the start of a 36 hour shut-down period and then again at the end and any differences compared. With this kind of manual tank gauging the site must be shut down (USEPA OSWER, 1989: p33).

Inherent to both these methods is a potential for large errors. Any losses or gains can be due to temperature differences, evaporation or water entering the tank and not necessarily a leak. There is considered to be a 0.03% margin of error under even the best operating practices (Environment Agency, 1996b: p31) and it is not considered a suitable method of leak detection at sites within a groundwater protection zone.

An alternative to these methods is automatic tank gauging (ATG) where the gauge is installed in the tank and there is no need for personnel to manually dip a tank. ATG systems can operate continually in 'inventory mode' to measure deliveries etc. and in 'leak detection mode' when the site is shut down (e.g., overnight). Both modes can take account of temperature and water in the tanks. An ATG system in 'leak detection mode' can be used to supply data for a continuous statistical leak detection system and in 'inventory mode' provide for automatic wet stock reconciliation (useful if the site is open 24 hours per day) (USEPA OSWER, 1989: p77).

Interstitial monitoring is only possible where an interstitial space is present: i.e. double-walls. It can be carried out for tanks and pipework. Tanks can use a 'wet system' where the space is filled with fluid and the level of that fluid is monitored. A dry system monitors for fuel vapour. Pipework systems can monitor for fuel, water or vapour. Interstitial monitoring is considered by the USEPA to be the best way of detecting leaks as they can be found before any fuel escapes into the environment (USEPA OSWER, 1989: p161). The Environment Agency requires interstitial monitoring of tanks and pipework in groundwater protection zones I and II and on tanks only in zone III (Environment Agency, 1996b: p36).

Monitoring wells can be installed at a site to detect fuel releases into groundwater or a vapour monitoring system can be used. The problem with both these types of system is that there has to have been a leak into the environment already for it to be detected.

In terms of risk to groundwater it is important to know what types of activities occur at a typical site, how the fuel is stored and distributed, leak detection methods used etc. It is equally important when trying to compare sites as part of a prioritisation scheme to know how fuel can be released in to the environment and which is most common.

### **3.3.2 Causes of Release of Fuel from Petrol-Filling Stations**

The causes of leaks and spills at a retail petrol-filling station are many and varied. Attention has traditionally focused on the storage of fuel, i.e. tank failure. In the USA, the USEPA carried out a preliminary survey in 1986 of underground storage tanks and found that 35% of tanks failed a tank-tightness test, implying that 35% of tanks leaked (Sun, 1986). This figure was disputed by the American petroleum industry who stated that "Even when leaks occur, they are typically detected and corrected before groundwater is affected and usually confined to the property of the tank system owner" (O'Keefe, 1986). This may be an overconfident statement as detecting leaks and estimating how big the leak is or how long it has been going on for is extremely difficult. Although methodologies have been developed to assess leakage rates and volumes from UST's, they must be used with care, with full knowledge of any assumptions used. For example, the technique developed by Levy, Riordan & Schreiber (1990) is only suitable for a subsurface of sand/gravels with a range of assumptions including that (i) the aquifer is homogenous, (ii) that it has a horizontal base that is impermeable, and (iii) that percolation begins instantaneously and is constant with time.

Further work carried out for the USEPA into the causes of leaks in underground storage tanks (UST's) prior to the development of the UST regulatory program disputes this industry stance, and illustrates some important points that are relevant to the UK situation (USEPA OSWER, 1987). The most significant findings of this data gathering exercise were that:

- Releases from delivery pipes and spills/overfills are a more numerous source of leaks than tanks
- Tank fittings, vent lines and fill pipes also leak more frequently than the tanks themselves
- Older 'bare' steel tanks fail most often due to corrosion, but introduction of FRP/GRP tanks or FRP/GRP coated steel tanks with cathodic protection has nearly eliminated external corrosion failures
- For pipework, failure can also be due to poor installation, accidents and natural events and not just corrosion
- If a 'pressure fuel delivery' system is used, large releases can occur unless line-pressure monitoring devices are utilised

When this study was carried out in 1987, there were estimated to be 1,318,000 UST systems in use in the USA. As of March 1997, there are considered to be approximately 1.1 million UST systems, with the possible closure of another 300,000 before the December 1998 deadline for site upgrading (USEPA OUST, 1997). The 1987 study identified that tank system leaks accounted for approximately 15 to 20% of all releases, with an average release of 2000 to 2500 litres of fuel. Spills, tank overfills, tank vents/fill lines and pipework leaks account for the other 80 to 85%.

The age of the tank system is important and a critical factor, especially for steel tanks. As steel tank failure is most often due to corrosion, the failure rate tends to increase with tank age. This only applies to steel tanks. Other types of tank such as GRP will tend to fail early in their operational lives and then generally due to leaky tank fittings or vents (poor installation) not the tanks themselves. Information supplied to the USEPA by Service Station Testing Inc. for the 1987 study, showed that of 214 GRP tanks tested, aged 0 to 14 years, no actual tanks leaked, but 8% of systems failed due to leaky tank fittings or vents. Nearly all these failures occurred in the first four years of operation. This can be contrasted with information from the same company about steel tanks. This information is summarised in Table 3.5.

**Table 3.5: Steel tank system failures (USEPA OSWER, 1987)**

Age of Tank System (years)	No. Tank Systems Tested	No. Leaks due to Tank Failures	No. Leaks due to Tank Fitting Failures	No. Leaks due to Tank Vent Failures	Total No. Leaks	Total no. leaks as % of no. tank systems in each age category
0-5	191	5	20	9	34	17.8
6-10	137	3	16	10	29	21.2
11-15	227	19	10	14	43	18.9
16-20	258	12	20	25	57	22.1
21-25	157	6	19	13	38	24.2
26+	43	3	0	0	3	7.0
<b>Totals</b>	<b>1013</b>	<b>48</b>	<b>85</b>	<b>71</b>	<b>204</b>	<b>20.0</b>

Pipework failures, even though in the USEPA 1987 study they constituted approximately 80% of all releases, were not so well documented as tank failures. The main causes of pipework failure are given as corrosion and leaking joint work often due to poor installation. There is also evidence to show that pipework will tend to leak in the early period after installation (less than 10 years) whilst problems with tanks typically occur later on (Osgood & Swokel, 1986).

Unfortunately there are several problems with using this type of data for comparison purposes as it not always stated which part of the tank system fails. In Table 3.5, there were 48 failures due to actual tank failures but 204 system failures overall. This must be considered when trying to compare data, especially from different operational regimes.

Petrol-filling stations in the UK have traditionally used single-skin steel underground tanks to store petroleum and diesel products (until relatively recently). Many of these tanks are 'bare' steel tanks or have a bitumen type surface coating and are susceptible to corrosion (even when surrounded by concrete). Tank and pipework age is an important factor. The pipework that forms a vital part of the fuel distribution system has traditionally used metallic pipes e.g. steel, with no secondary protection. A survey carried out in London in 1992, showed that over 52% of the tanks were over 20 years old with 18% over 30 years old. This survey also found that of the leaks that were discovered, 30% were caused by corroded tanks but 70% from the associated pipework. It has been estimated that oil companies only spend 5-7% of site development costs on underground tanks and pipes (Thompson, 1993).

In 1993 Shell UK stated that approximately one third of their 1,100 sites were contaminated to some degree. Leaks from fuel lines, single skin tanks, a lack of spillage detection and overspill protection were thought to of contributed to the problem (Anon, 1993b). A survey, also carried out in 1993 (Anon, 1993c) of local authority environmental health departments and fire authorities found nearly 300 leaks and spills that were known to of caused ground contamination. Unfortunately the causes of such incidents were not requested but where information was provided, the main cause was leaking pipework followed by spills, overfills and leaking tanks. Quantitative data also supplied as part of the survey contradicted this, with tank leaks being more common than pipework leaks but this only covered 78 of the 300 cases. An interesting finding of the survey was that the flow of information from fire authorities to environmental health departments with regard to petrol spills and leaks was poor but information flow was much better in the other direction (86% of incidents dealt with by environmental health departments were passed on to the petroleum officer).

There is no central database of information about USTs in the UK, however it has been estimated that there are approximately 50,000 tanks in the UK (with approximately 2000 of those being made of GRP) (Thompson, 1997).



In summary, the key parameters which can be important in assessing site-specific risk are:

- type of fuel that is stored and may be released e.g., petroleum or diesel - will affect solubility in water, viscosity etc. and hence movement in unsaturated zone
- presence of fuel additives such as MTBE
- volume of release - small volumes may be attenuated
- groundwater flow rate
- rate of adsorption of hydrocarbon onto soil particles
- biodegradation rate of hydrocarbons
- rate of volatilisation of hydrocarbons
- soil type
- partition coefficients for hydrocarbons e.g. benzene, MTBE
- tank/pipework construction
- tank/pipework age
- corrosion protection for tanks/pipework
- spill protection on delivery/dispensing
- leak detection system utilised at the site

## CHAPTER 4

### 4 RISK MANAGEMENT OF POINT- SOURCE HYDROCARBONS - AN OVERVIEW

#### 4.1 INTRODUCTION

The previous chapter discussed hydrocarbons (particularly petroleum and diesel) as potential pollutants of groundwater. A common point-source of such pollutants in the UK are petrol-filling stations. These type of sources and the risk they present to the groundwater environment can be managed under the common framework of risk management. The risk-based approach to site assessment and management is of course not restricted to these types of contaminants and sites.

An understanding of how a risk-based approach can be used with regard to point-source hydrocarbons is gained by consideration of the historical development of environmental policy in the UK. In the past, environmental management has been governed by a 'reactive approach' or on the basis of 'when the need arises' (e.g. Petts, Cairney & Smith, 1997: p18). Recently, however, a more 'proactive' risk-based approach has been introduced. These differences of approach can be demonstrated by investigating the issue of groundwater protection and contaminated land management in the UK (sections 4.2.1 and 4.2.2).

There is a need, however, for such a risk-based proactive approach to be based in the policies, functions and regulatory controls of the government body charged with such duties: i.e. the Environment Agency (in England and Wales). Chapter 2 discussed the risk concept in theory, this chapter illustrates a risk-based approach in practice i.e. how the Environment Agency functions and how the regulatory framework operates with particular reference to the contaminated land regime, petroleum and petrol-filling stations.

As an introduction to this research, the Chapter concludes with current risk-based methods that are available in the UK and elsewhere and some comments on the deficiencies of these existing management methods.

#### 4.2 CURRENT AND PAST APPROACHES TO THE PROBLEM

##### 4.2.1 The Past Reactive Approach

The study of groundwater protection and pollution is inherently tied into the way contaminated land is viewed in the UK and how it has been dealt with in terms of government policy. Contaminated land *per se* is recognised as not being a new problem but has generally been managed in the past via the planning control system in the UK. It is only relatively recently that it has emerged as a matter worthy of concern in its own right. In terms of groundwater

pollution, landfills have often been seen as the most important source (e.g. Department of the Environment, 1978). Again, it is only recently that landfills have been acknowledged as being just one of many different types of source that may have a significant impact on the groundwater environment (Anon, 1997a).

There have been a number of well-known incidents around the world that have raised the public profile of contaminated land and associated potential environmental effects such as at Lekkerkerk in the Netherlands (1975), Love Canal in the US (1978) and Loscoe in Derbyshire (1986) (Tromans & Turall-Clarke, 1994: p1).

Before the formation of the Environment Agency water-based 'issues' came under the control of the National Rivers Authority (and the Water Authorities before that) and land quality 'issues' under one of the Waste Regulation Authorities or Planning Authorities. There were no direct policy links between such bodies which led to an uncoordinated approach to the management of contaminated land.

The reactive approach to the management of contaminated land has been characterised by either the need for land for redevelopment, or public concern over a particular site. There was no real attempt to proactively identify sites that may be contaminated and may pose a risk to human health or the environment in the future. In the UK, the increasing profile of contaminated land resulted in the issue of specific technical guidance in 1983 by the Interdepartmental Committee on the Redevelopment of Contaminated Land (ICRCL). This government body issued a document on the assessment and redevelopment of contaminated land, with a second edition in 1987 (ICRCL, 1987). This document gave 'action' and 'threshold' values based on land-use for a range of soil contaminants. These values were used, for example, by officers in the waste regulation authorities to decide whether land was contaminated or not, often with no understanding of how or why the values had been derived. In 1987 the Department of the Environment issued a circular on contaminated land that provided advice and guidance to local authorities, developers etc. on the identification, assessment and development of contaminated land (Department of the Environment, 1987). A draft British Standard was also issued in 1988 (BSI, 1988) giving guidance on the identification and investigation of contaminated land but this document has remained as a draft and has not been issued as an official British Standard.

The UK, whilst not unique in adopting a reactive approach to contaminated land issues in the past has deviated from approaches taken in other countries such as: the USA (Weiner, 1993); the Netherlands (Vegter, 1993); Denmark (Poulsen, Vendelboe & Holm, 1993); Austria (Kasamas, 1994); and Canada (Hofmann *et al.*, 1993).

In addition to the political impact of major incidents such as Love Canal etc., another reason for the change from a reactive to a more proactive approach to the management of contaminated land in the UK (and elsewhere) was the concept of 'sustainable development'.

#### **4.2.2 The New Proactive Approach**

Fundamental to a proactive approach to groundwater protection and contaminated land management is the concept of 'sustainable development'. In 1972 the United Nations held a conference on the "Human Environment" which aimed to "delineate the 'rights' of the human family to a healthy and productive environment" (World Commission on Environment and Development, 1987: pxi). In 1987, the concept of 'sustainable development' extended these 'rights' through the definition in the World Commission on Environment and Development report, 'Our Common Future' (also referred to as the Brundtland Report): i.e. "to ensure that it [development] meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development, 1987: p8). Following on from this, the Earth Summit held in Rio de Janeiro in 1992 (UN Conference on Environment and Development) produced the 'Agenda 21' programme of action to achieve sustainable development (United Nations, 1992).

One of the principles of Agenda 21 is the 'precautionary approach' (United Nations, 1992: p10) and one chapter of Agenda 21 is dedicated to water protection with a 'Programme Area' entitled "Protection of water resources, water quality and aquatic ecosystems". The objectives of this programme area introduce the 'catchment management approach' to freshwater management (including groundwater) and recognise that "The extent and severity of contamination of unsaturated zones and aquifers have long been under estimated .... The protection of groundwater is therefore an essential element of water resource management" (United Nations, 1992: p172). Agenda 21 encourages the implementation of these objectives via a set of suggested activities such as the application of the 'polluter pays' principle and the use of risk assessment and risk management in a decision-support role. Those activities specific to groundwater protection have clearly influenced policy development in the UK and include:

- Development of agricultural practices that do not degrade groundwaters
- Prevention of aquifer pollution through regulation of toxic substances that permeate the ground and the establishment of protection zones in groundwater recharge and abstraction areas
- Design and management of landfills based upon sound hydrogeologic information and impact assessment, using the best practicable and best available technology

In 1990 the Government issued a White Paper entitled "This Common Inheritance - Britain's Environmental Strategy". Contaminated land (as opposed to just derelict land) was recognised

as being difficult to "define and measure exactly ... and that the nature of the contamination and the possible risks to health and groundwater supplies vary widely" (Anon, 1990: p92). In order to manage this, "registers of land that may be contaminated" were proposed and had already been incorporated into what was then the Environmental Protection Bill. The development of registers of contaminated land was not a new proposal and in Wales a national survey of contaminated land had been carried out in 1984 and updated in 1986 (Welsh Development Agency, 1986). This approach was not extended to the rest of the UK at that time. The relevant section (43) of the Environmental Protection Act 1990 was never enacted due to the fear that land would be blighted and therefore lose value if it was put onto such a register (Harris, 1993). The basis of inclusion on this proposed register rested on the previous use of the land and whether that use was a specific 'contaminative use' and not whether on investigation, the land was *actually* contaminated.

In response to the UN Agenda 21 document, the UK produced its own sustainable development strategy in 1994 (Anon, 1994a) on which Environment Agency policy is based. The protection of groundwater from pollution is recognised (p62) as is contaminated land being a source of that pollution (p9). In addition, the Royal Commission on Environmental Pollution (RCEP) recommended that soil should be accorded the same priority in environmental protection as air or water (RCEP, 1996).

The Department of the Environment (now DETR) also has sustainable development as an objective and one of the main achievements reported by the department for 1997 was the issuing of the contaminated land regulations and guidance for consultation (Department of the Environment, 1997: p109) under the new Environment Act (1995).

The Environment Act, 1995 (section 57) introduces a new section (78A) into the Environmental Protection Act, that deals specifically with the definition and identification of contaminated land. This new piece of legislation was developed after the Government carried out a policy review in 1993 which included consultation on a document called 'Paying for Our Past' (Department of the Environment, 1994a). The outcome of this process was a 'Framework for Contaminated Land' (Department of the Environment, 1994b: p4) which lays down the Government's objectives for dealing with contaminated land that are implemented by section 57 of the Environment Act, 1995. Fundamental to this process is the 'suitable for use' approach where remedial action is only required if:

- the contamination poses unacceptable, actual or potential significant risks to health or the environment; and
- there are appropriate and cost-effective means available to do so, taking into account the actual or intended use of the site.

Therefore under the Environment Act, contaminated land is:

"any land which appears to the local authority in whose area it is situated to be in such a condition, by reason of substances in, or under the land, that -

- (a) significant harm is being caused or there is a significant possibility of such harm being caused; or
- (b) pollution of controlled waters is being, or is likely to be caused"

Draft guidance has been issued by the Government in order to assist local authorities and other regulatory bodies such as the Environment Agency in the interpretation of this new regime, for example, how to define significant harm and what targets (receptors) may be considered (Department of the Environment, 1996b). At the time of writing, this new regime governing identification and control of contaminated land has not yet been enacted and the earliest implementation date is now July 1999 (Anon, 1998a).

The first step in deciding whether groundwater is polluted or land is contaminated (irrespective of the definitions used) is to actually identify the site (Petts, Cairney & Smith, 1997: p18). The reactive approach involves dealing with a site on the basis of need e.g., redevelopment of the site, or when members of the public complain about a site. A proactive approach, however, also involves the development of a formal system to identify and survey all sites which may be contaminated in an area. The new UK regime is based on the source-pathway-target model and is inherently risk-based. To support this new regime, what was the Department of the Environment commissioned a series of "standard procedures for the management of contaminated land, within an overall risk management approach" (Herbert, Harris & Denner, 1995). At the time of writing, these risk management procedures have not been published. Other types of supporting guidance, however, has been published, for example the CIRIA guidance documents for construction on contaminated land (Johnson *et al.*, 1993, CIRIA, 1995).

Petts, Cairney & Smith, (1997: p18) have identified several requirements of a proactive approach to site identification in terms of land contamination, as follows:

- (a) priorities to be identified in terms of land-uses which may present significant contamination;
- (b) systems to be devised, so that sites can be identified on a consistent basis;
- (c) the development and management of systems to hold information on land where contamination is suspected or confirmed; and
- (d) development of prioritisation tools to identify those sites that should be investigated further or where resources should be concentrated.

It is the latter that has been one of the major objectives of this research.

Petts, Cairney & Smith, (1997: p22) have also identified two different but complimentary approaches to the assessment of the significance of risk, or, whether a site is contaminated to such an extent that action is required:

- (i) generic approach - guidelines and standards are developed to be applied to all sites;  
and
- (ii) site-specific approach - site-specific criteria are developed on a site-by-site basis using actual hazards and exposures from each site

A generic approach has several advantages such as convenience and relatively low data requirements (Petts, Cairney & Smith, 1997: p23) and has therefore formed the basis of several risk-based assessment models discussed in section 4.4. A generic approach, however, should not be used as a substitute for site-specific assessments just because it is easier or cheaper to carry out, as the outcome may not be acceptable in terms of risk to the environment or it may be over-protective, and wasteful of resources.

Generic values can be developed for a particular media e.g., water or soil and can exist as guidelines (non-statutory use) or as standards where they must be applied. In the UK, guideline values for soil were developed by the Interdepartmental Committee for the Redevelopment of Contaminated Land (ICRCL, 1987). The basis for the values that were derived (only a limited number of substances were included) was the ultimate use of the land in question; open space, industrial or residential. New risk-based guidelines are being developed to replace the ICRCL values using the Contaminated Land Exposure Assessment (CLEA) model (Ferguson & Denner, 1993). Currently, however, CLEA considers risk to humans and is a model to derive *soil* screening guidelines only (Petts, Cairney & Smith, 1997: p220).

In the Netherlands, several sets of guidelines have been developed over the years which focus on 'soil' protection. Soil concentration may indicate an acceptable level of contamination of groundwater when in fact this is not the case (e.g. Eastwood *et al.*, 1991). This has resulted in the Netherlands in the development of 'intervention' values for soil concentrations which are protective of groundwater (Henning, 1993).

#### **4.2.3 The Environment Agency - Policy and Functions**

The Environment Agency for England and Wales was set up in 1995 by means of the Environment Act 1995, and took up its duties in April 1996. The Environment Agency is an independent body that took over the responsibilities carried out formerly by the National Rivers Authority (NRA), Her Majesty's Inspectorate of Pollution (HMIP), some sections of the

Department of the Environment and Local Authority Waste Regulation Authorities. A similar function is carried out in Scotland by the Scottish Environmental Protection Agency (SEPA). The Environment Agency is a regulatory body and has a statutory responsibility "to protect or enhance the environment ... to make the contribution towards attaining the objective of achieving sustainable development ... " (Environment Act, 1995, section 4 and Environment Agency, 1996a: p4).

The Environment Agency has taken on the responsibilities of its predecessor bodies but has also been given new duties. These include: compiling 'State of the Environment' reports; taking account of the costs and benefits of pollution control; encouraging producer responsibility; and disseminating information to industry and the public.

The Government has issued specific guidance to the Environment Agency to ensure that its work is carried out with due consideration of sustainable development. This guidance includes such statements as "decisions should be based on the best possible scientific information and analysis of risks" and "high quality information and advice should be used by the Agency and provided to others" (Environment Agency, 1997a: p25). This guidance has been developed into a series of 'strategic objectives' (Environment Agency, 1996a: p5):

- to adopt, across all its functions, an integrated approach to environmental protection and enhancement, which considers the impact of substances and activities on all environmental media and on natural resources;
- to work with all relevant sectors of society, including regulated organisations, to develop approaches which deliver environmental requirements and goals without imposing excessive costs (in relation to benefits gained) on regulated organisations or society as a whole;
- to adopt clear and effective procedures for serving its customers, including the development of single points of contact through which regulated organisations can deal with the Agency;
- to operate to high professional standards, based on sound science, information and analysis of the environment and of the processes which affect it;
- to organise its activities in ways which reflect good environmental and management practice and provide value for money for those who pay its charges and for taxpayers as a whole;
- to provide clear and readily available advice and information on its work;
- to develop a close and responsive relationship with the public, local authorities and other representatives of local communities and regulated organisations.

These objectives are repeated here in full as they emphasise a change in the regulatory environment and approach from the Agency predecessor bodies: i.e. from a reactive to more of



a proactive approach. The Environment Agency aims to become 'a one-stop-shop' for industry (it's customers). In addition, the cost and benefits of environmental protection must be specifically accounted for by the Agency. This is the first time in the UK that such a body has been formed, with these kind of objectives for environmental regulation and management. Such an approach is not new however, the United States Environmental Protection Agency operates to similar principles and has been in existence since 1970.

The Environment Agency is described as a "non-departmental public body" (Environment Agency, 1996a) with direct links to the Department of the Environment, Transport and the Regions (DETR), Ministry for Agriculture Fisheries and Food (MAFF) and the Welsh Office. There are three broad layers of management: head office, regions and areas. Head office is responsible for policy issues, setting of standards etc., the regions and areas have operational responsibility. There are eight regions with twenty-six areas. The Agency is a large complex body which can have implications for communication, for example, between individuals from different regions. This may also impact on the implementation of policies and decision-making strategies on a national basis.

In trying to achieve its objectives, the Environment Agency has developed a set of regulatory and environmental management functions, with the protection of groundwater as an inherent part of those policies. Specific relevant objectives include the following (Environment Agency, 1996a: p10)

- regulation and the remediation of contaminated land designated as special sites;
- regulation of the treating, keeping, movement and disposal of controlled waste, to prevent pollution of the environment or harm to public health, in a manner which is proportional to the threat posed;
- preservation or improvement of the quality of rivers, estuaries and coastal waters through its pollution control powers;

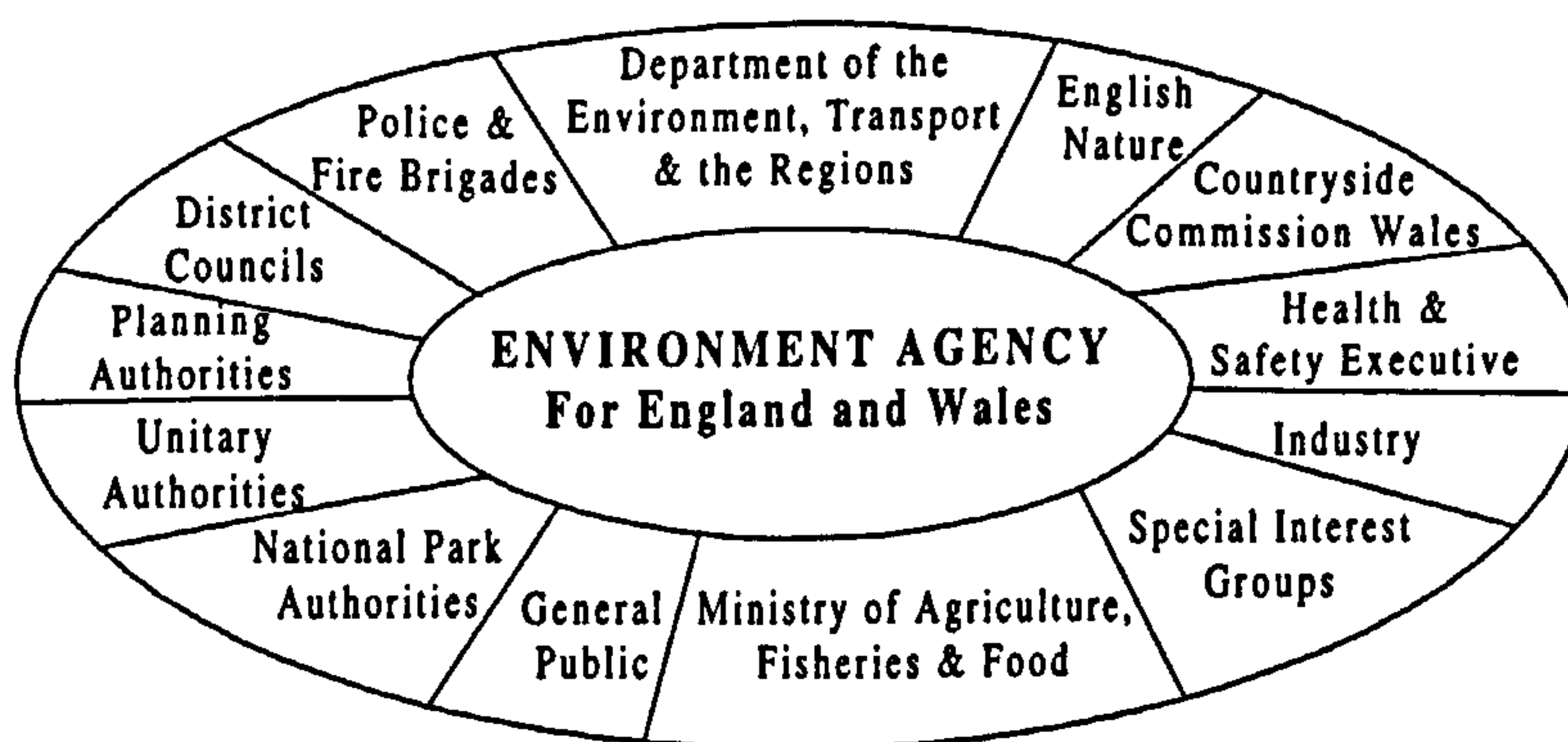
The Agency also has "monitoring, assessing, reporting and advising" functions that impact on the management of contaminated land and groundwater protection, such as to (Environment Agency, 1997a: p27)

- assemble environmental data, from its own monitoring and other sources ..... and form an opinion of the general state of environmental pollution
- report on the state of contaminated land and produce site-specific guidance to local authorities on dealing with contaminated land
- monitor pollution of freshwater and groundwater

There is great emphasis on regulation in proportion to the 'threat' posed which is inherently part of a risk-based approach to pollution prevention and control. The implementation of which is stated as a target in the Environment Agency Corporate Plan for 1997/98 (Environment Agency, 1996c: p7). Many Agency objectives and functions have a direct link to point-sources of hydrocarbon groundwater pollution such as petrol-filling stations, for example, the identification and remediation of contaminated land and the protection of water resources. Some particularly pertinent Agency aims in relation to petrol-filling stations that can be found in the Agency's Environmental Strategy (Environment Agency, 1997a: p14 & 18):

- *'Conserving the Land'*
  - influencing the Town and Country Planning System to prevent developments in the wrong place
  - to work with local authorities to identify and report on the extent of contaminated land
  - to regulate identified 'special sites' effectively
  - to research into the specific risks and remediation needs of contaminated land
- *'Managing Water Resources'*
  - to vigorously apply the Groundwater Protection Policy to ensure that quality and use of groundwaters is improved

The Environment Agency does not carry out its duties in isolation and it must interact with other bodies and individuals. The Agency's Environmental Strategy document actually states that the Agency will: (i) "operate openly and consult widely upon decisions and actions"; (ii) "work with industry to ensure that industry itself benefits from the need to protect the environment"; and (iii) "influence politicians, the public, industry and our fellow regulators in order to achieve a better and sustainable environment" (Environment Agency, 1997a: p7).



**Figure 4.1:** The Environment Agency and some of the other bodies it must interact with (adapted from NRA, 1992: p1)

The types of body and individuals that the Agency must interact with are many and varied (Figures 4.1 and 4.2). This can sometimes lead to conflict as each body (or individual) has its own agenda and may have its own guidance (e.g. Planning Authorities are guided by PPG 23 in

pollution control matters (Department of the Environment, 1994e). With such a diverse organisation like the Environment Agency, which must interact with others, decision-making and especially risk-based decision-making i.e., systematic, rational and transparent decision-making, sometimes becomes difficult.

Figure 4.2 illustrates how the Environment Agency must respond to and interact with some of the other bodies and individuals shown in Figure 4.1.

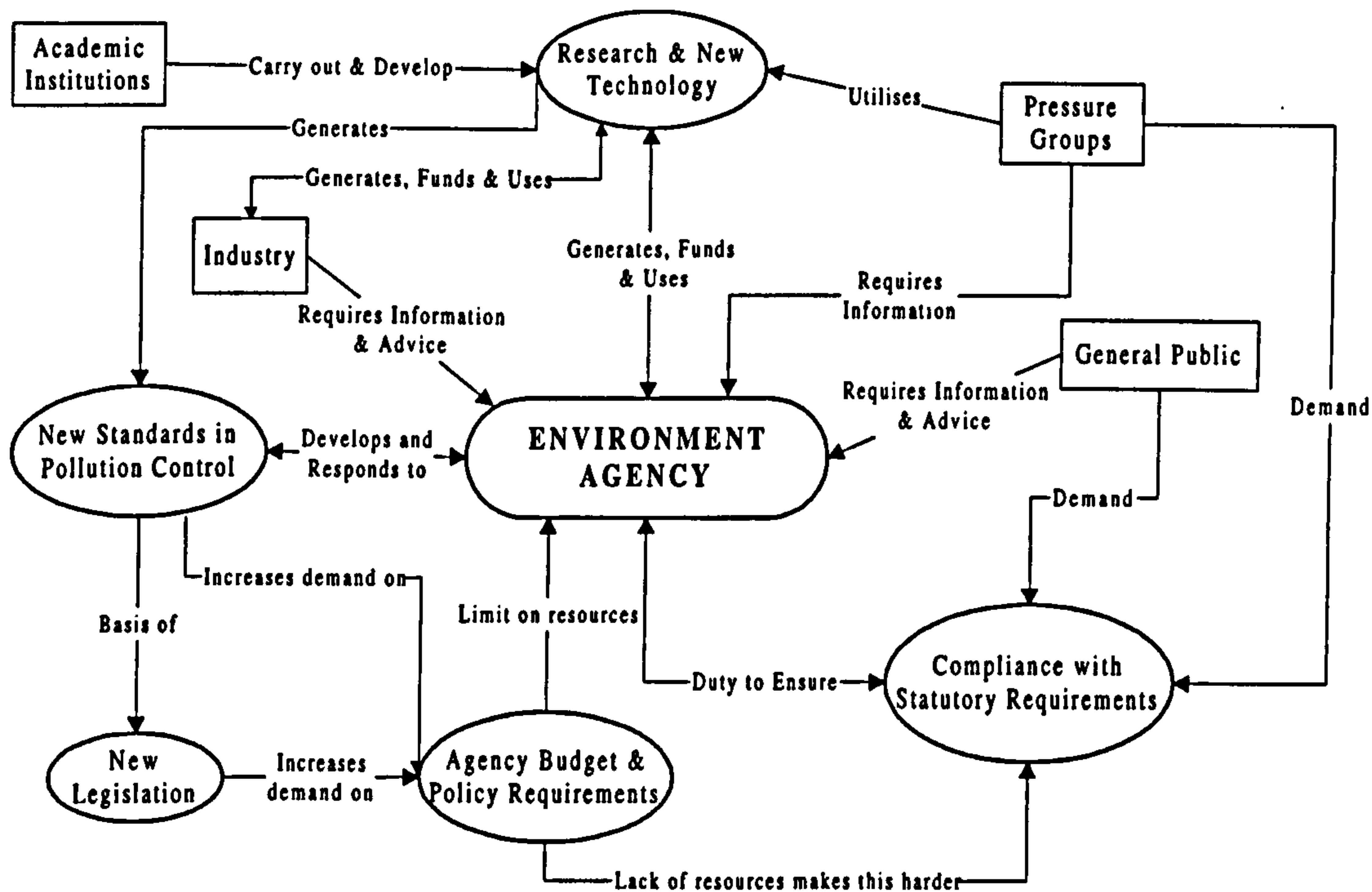


Figure 4.2: The Environment Agency - some possible types of interactions with other bodies and individuals

*Groundwater Protection Policy and the Environment Agency*

The primary piece of legislation governing groundwater protection in the UK is the European Directive 80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances. The Directive focuses on certain "toxic, persistent and bioaccumulable substances" and to ensure effective groundwater protection, the discharge of List I substances is prohibited and the discharge of List II substances is limited and must be authorised in some way (List I and II substances are shown in Table 4.1). Exceptions to this include " ... discharges containing substances in Lists I or II in very small quantities and concentrations, on account of the low risk of pollution ...".

In the UK, compliance with this Directive was relatively slow, initially coming under 'consent for discharges' in the Control of Pollution Act 1974, which was not fully enacted until 1984.

However, a Circular was issued in March 1982 by the Department of the Environment (Department of the Environment, 1982) giving guidance to water authorities, waste disposal authorities etc. on how to interpret the Directive. This Circular implied that existing legislation was sufficient to comply with the Directive (which was not the case) and that substances should only be classified as List I if there was proof of toxicity, persistence or bioaccumulation - an incorrect 'interpretation' of the Directive which compromised the 'pollution prevention' aim of the Directive. In 1990, a second Circular was issued (Department of the Environment, 1990) reversing that advice and reinstating the 'precautionary principle' i.e. all substances included in List I were to be considered as such until evidence was gathered to prove otherwise. List I and II substances are shown in Table 4.1, mineral oils and hydrocarbons being List I substances.

**Table 4.1: EC Groundwater Directive 80/68/EEC - List I and II substances**

<b>List I (prohibited for discharge)</b>	<b>List II (limited for discharge)</b>
Organohalogen compounds and substances which may form such compounds in the aquatic environment Organophosphorous compounds Organotin compounds Substances which have carcinogenic, mutagenic or teratogenic properties in the aquatic environment Mercury and its compounds Cadmium and its compounds Mineral oils and hydrocarbons Cyanides	Metals, metalloids and their compounds: zinc, copper, nickel, chrome, lead, selenium, arsenic, antimony, molybdenum, titanium, tin, barium, beryllium, boron, uranium, vanadium, cobalt, thallium, tellurium, silver Biocides and derivatives not appearing on List I Substances that can adversely affect the taste/odour of groundwater making it unfit for human consumption Toxic or persistent organic compounds of silicon and substances which may cause the formation of such compounds in water (except harmless ones) Inorganic compounds of phosphorous and elemental phosphorous Fluorides Ammonia and nitrites

The Directive is now implemented in the UK by several pieces of legislation such as the IPC and waste management functions of the Environmental Protection Act, 1990 (including the Waste Management Licencing Regulations, 1994), the discharge consent and water protection zone designation functions of the Water Resources Act, 1991 and consultation with the relevant planning authorities under the Town and Country Planning Act, 1990.

In 1992, the NRA issued the National Rivers Authority Policy and Practice for the Protection of Groundwater (NRA, 1992) which is essentially a pollution preventative measure and could be termed proactive in its approach to controlling groundwater pollution (in compliance with Agenda 21). This document was an attempt to co-ordinate the statutory responsibilities of the NRA (now responsibilities of the Environment Agency, Haigh, 1995: p4.7). A second edition has now been issued (Environment Agency, 1998) but remains essentially the same as in 1992. It is not statutory guidance however. The fundamental principle underlying this policy is 'sustainable groundwater use'. The Environment Agency has a duty to protect and monitor

groundwater, conserve it as a water resource and maintain/enhance conservation of surface water (Environment Agency, 1997a).

The Policy and Practice for the Protection of Groundwater (Environment Agency, 1998: p12) has several objectives:-

- (i) to ensure that all risks to groundwater are dealt with in a common framework
- (ii) to provide a common basis for decisions affecting resources within and between regions
- (iii) to encourage a standard approach between the Environment Agency and other bodies

The fundamental principle underpinning these objectives is a consistency of approach. So an officer in one region presented with a similar problem to an officer in another region, even though the sites are different, will use the same method to arrive at a solution in a consistent manner. The lack of formal risk assessment procedures and the inherently complex nature of many of the decisions to be made regarding groundwater protection can lead to a lack of consistency in decision-making. Officers who are not perhaps fully aware of all aspects that need consideration, still have to make decisions and the number of experts available to provide guidance at any one time may be limited.

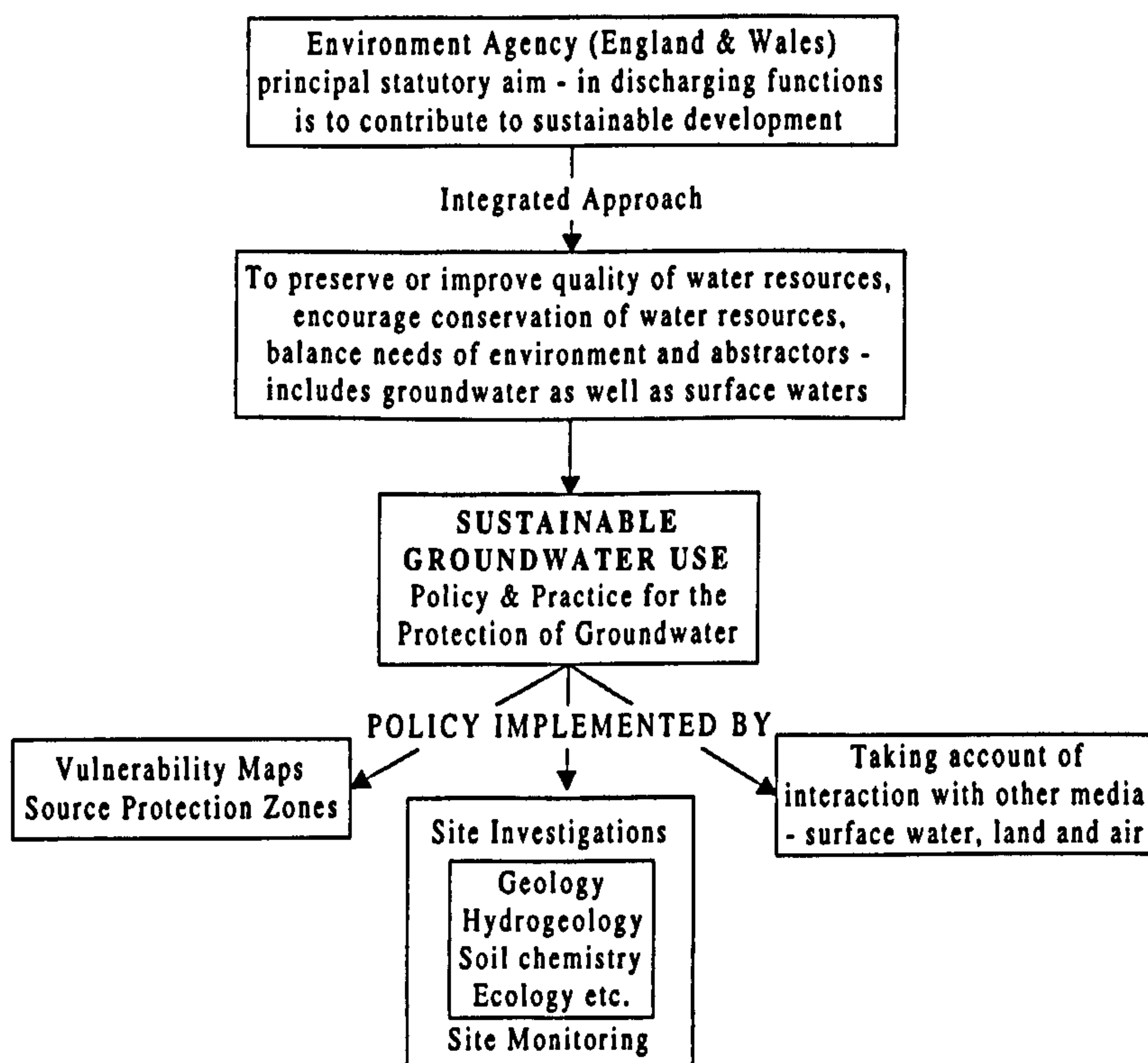


Figure 4.3: Groundwater protection policy, aims and implementation

According to the policy document (Environment Agency, 1998: p3) sustainable groundwater use and a consistent approach to decision-making will be implemented by the development of groundwater vulnerability maps and source (groundwater) protection zones (described by Adams & Foster, 1992). This work is now well advanced and a series of vulnerability maps and source protection zones have been published, as has guidance to their interpretation (NRA, 1995a; NRA, 1995b). Information such as that given by a groundwater vulnerability map is designed to be supported by site specific information, such as site geology, soil data, hydrogeology, geochemistry and ecology. This kind of information can be gathered via site investigations and site monitoring (Figure 4.3).

Many new developments and existing activities do not conform to this policy, so the Environment Agency must be able to identify those activities and facilities that require most attention, in areas of the country where groundwater resources are most important. The policy provides a framework that allows new developments and existing activities to be assessed on the basis of risk to groundwater and this allows regulatory effort to be targeted more effectively (Harris, 1997).

The backbone of the Groundwater Protection Policy are the Groundwater Vulnerability Maps and the Source Protection Zones. The concept of groundwater vulnerability as stated by the NRA is "the susceptibility of groundwater to contamination from surface or near-surface derived pollutants, recognises that the risk of pollution from a given activity is greater in certain soil and hydrogeological situations than in others" (NRA, 1995b: p3). The factors which define groundwater vulnerability are:

- presence and nature of overlying soil (particularly leaching potential)
- presence and nature of drift deposits
- nature of the solid strata
- depth of the unsaturated zone

These criteria have been used to generate the vulnerability maps of England and Wales and are not site-specific, full quantitative risk assessments but can be used as part of an initial site screening or prioritisation process. Their use was aimed at protecting groundwater as a resource (not just as a source of drinking water) (Environment Agency, 1998: p18).

The Groundwater Protection Policy also uses the designation of 'Source Protection Zones' (SPZ) in order to reduce risks to groundwater abstraction points for drinking water, although the policy does recognise that other targets require protection too. The key factor when assessing the risk to a groundwater source is the proximity of an activity to that source (Mumma, 1995: p48). Three zones can be designated (Environment Agency, 1998: p23):

- Inner source protection, Zone I - located immediately around the source (i.e. the abstraction point) where activities may have an immediate effect on the abstraction. The area is defined by a 50-day travel time from any point in the saturated zone to the source (minimum is 50m)
- Outer source protection, Zone II - larger than zone I and defined by a 400-day travel time from any point in the saturated zone to the source
- Source catchment, Zone III - covers the complete catchment area for that groundwater source. The size of Zone III will depend on the volume of water abstracted and the aquifer replenishment rate and could be a few kilometres for a Triassic sandstone but may be much bigger for a Chalk aquifer.

Source protection zones have been used by the Environment Agency to generate guidance relating to specific types of land-use such as petrol-filling stations, such as the type of tanks that should be used etc. (Environment Agency, 1996b). The requirements described by this guidance document are compared to those demanded by the USEPA for US tank owners in section 4.2.4 and Table 4.2.

The Groundwater Protection Policy (Environment Agency, 1998) recognised seven types of activity that could pose a threat to groundwater, contaminated land being one of them (which includes hydrocarbon storage) and a specific set of policies was presented for contaminated land (p35). These policies were intended to cover re-development of contaminated land and currently active industrial sites. There is also an emphasis on encouraging the siting of new activities on non-aquifers if List I or II substances were involved (hydrocarbons being on List D). If such new sites were proposed within source protection zones, extra protective measures would be required such as minimising the underground storage of List I substances (petrol/diesel) and the prohibition of such storage in a Zone I area. This can of course only apply to new activities and is not statutory anyway.

The recent Environment Agency report 'Groundwater Pollution - Evaluation of the Extent and Character of Groundwater Pollution from Point Sources in England and Wales' (de Hénaut *et al.*, 1997) goes some way to identifying those point-sources of pollution that present the greatest threat to groundwater quality. Hydrocarbons and petrol-filling stations being one of those sources. Petroleum hydrocarbons as a specific risk to groundwater were discussed in Chapter 3.

Although the Groundwater Protection Policy is the major piece of guidance governing the way the Agency manages the groundwater environment it is not statutory guidance. There are, however some statutory requirements that exist in the UK specific to point-sources of groundwater pollution such as petrol-filling stations.

#### 4.2.4 Point-Source Hydrocarbons - Statutory Controls

In the UK, the keeping of petroleum must be licensed under the Petroleum (Consolidation) Act 1928 and The Petroleum (Transfer of Licences) Act 1936. Under the 1928 Act a licence must be obtained to allow petroleum to be stored and this licence can have conditions attached to it. The 1936 Act allows that licence to be transferred to a new operator. In effect the storage tanks are licensed. Licence conditions should follow guidance given by HSE (1990). Conditions can relate to the safe keeping of petroleum, preventing spills, leaks etc. The licensing authorities are the fire and civil defence authorities in metropolitan areas and county councils everywhere else (usually the Fire Brigade). Licensing authorities can refuse to issue or renew a licence and can modify the conditions. Emphasis is still very much on safety and not pollution control and this legislation only applies to petroleum tanks and not to diesel tanks. Recently, the Health and Safety Commission has put forward a proposal for consultation that will replace the 1928 and 1936 Acts (Anon, 1997b). It is proposed to abolish the current licensing system and instead require operators to obtain a 'consent' from the authorities to construct a new site or make significant changes to an old one. The possible environmental implications of this legislative change are not known at the time of writing.

Groundwater is, however, protected from hydrocarbons largely by legislation introduced to implement the Groundwater Directive (EC Directive 80/68/EEC): i.e.

- Part I of the Environmental Protection Act 1990 requires that IPC processes be authorised by the Environment Agency. The operation of an oil refinery would be an IPC process and before an authorisation is issued the potential impact of the process on surface and groundwater would be assessed.
- Under Part II of the Environmental Protection Act 1990, any land used for the management of controlled waste e.g. treatment of waste oil, requires a waste management licence. Again, before a licence is granted the potential impact on surface and groundwater would be assessed. Waste management licences can only be granted for waste management operations. If the material in question is not waste then a licence can not be issued. So the storage of hydrocarbons such as solvents may pose a significant risk to groundwater but need not be licensed (unless it is *waste solvent*). Storage areas must comply with Health and Safety legislation but this is focused on health and safety of humans not the environment (e.g., Health and Safety at Work Act, 1974 and the Control of Substances Hazardous to Health Regulations, 1988).
- Measures protective of the groundwater environment were also introduced by Regulation 15 of the Waste Management Licensing Regulations 1994 (SI No. 1056).



This governs assessment of the risk arising from the disposal or discharge of List I and II substances (hydrocarbons being a List I) from a site with a Waste Management Licence e.g. landfills.

- Under Part II of the Water Resources Act 1991 it is an offence to discharge polluting matter into controlled waters (which includes groundwater) without a consent issued by the Environment Agency. Under this legislation, a petrol-filling station should have an adequate drainage system with an interceptor and a consent to discharge.

A further set of regulations is currently at the consultation stage entitled "The Groundwater Regulations 1998" (DETR, 1998). These regulations will place a duty on the Agency to "issue notices prohibiting or controlling activities in or on the ground involving List I or II substances". These regulations are likely to have an impact on a wide variety of industries and fuel storage is specifically listed, as are underground tanks. The regulations are aimed at indirect discharges to groundwater such as disposal of sheep dip and will enable such a process to be authorised (these regulations will not apply to those activities already covered under IPC etc.). Those carrying out activities such as "...handling, storing or otherwise using List I substances ... do not have to apply for an authorisation ... they must however take the necessary technical precautions to prevent any indirect discharge of a List I substance to groundwater". Failure to comply could result in a service of a Notice and eventually prosecution for groundwater pollution. Interestingly the storage and use of List I chemicals in "unsatisfactory containment facilities, which might lead to groundwater pollution" is specifically mentioned as a reason why a Notice might be served. This will clearly impact on the storage of fuel at retail petrol-filling stations although the Agency will still have to provide evidence that indirect discharge of a List I substance could occur and if a release has occurred, before serving a Notice, where the release came from.

This legislation is still at the consultation stage at the time of writing but has generated a considerable amount of debate and criticism, particularly from the agricultural community in relation to the use and disposal of sheep dip (Anon, 1998b).

It is clear that statutory control of potential sources of hydrocarbon groundwater pollution such as petrol-filling stations is not particularly co-ordinated in the UK. Various bodies may have an input to any one particular site, e.g. Environment Agency, environmental health officers and planning officers from the local authority, petroleum licensing authority, Health and Safety Executive etc. Regulation falls to a variety of bodies each with their own agenda. This can lead to conflict or lack of communication, increasing the chances of inconsistent or poor decision-making.

Other countries such as the USA are trying to deal with this problem of inconsistent or poor decision-making in a relatively novel way. Groundwater supplies approximately 50% of drinking water in the USA and is seen as a resource that requires strong statutory protection from activities such as the underground storage of petroleum (USEPA OSWER, 1995). This was recognised in 1984 when Subtitle I was added to the Resource Conservation and Recovery Act (RCRA) which required an UST (Underground Storage Tank) regulatory program to be developed. Final regulations were issued in 1988 and it was estimated that there were about 1.1 million tanks requiring registration at approximately 400,000 sites (USEPA, 1988). The essence of the regulations are to: prevent releases, detect releases, and clean-up releases where they do occur.

It was considered impossible to successfully register and monitor so many tanks at a Federal (central) level along traditional regulatory lines. Regulation has been devolved to the State level and is not centrally based (USEPA OSWER, 1996). The USEPA Office of Underground Storage Tanks (OUST) was created as a Federal level body to provide technical advice and support to tank owners and State regulators. The US and UK requirements for control of leaks, spills etc. from underground storage tanks are compared in Table 4.2.

By March 1997, over 300,000 leaks had been confirmed with about half having some impact on groundwater (USEPA OUST, 1997). As part of the Federal tank program, efficient use of resources (financial and technical) was clearly important especially in directing the clean-up program. Risk-based decision-making is used and implemented by the RBCA standard (Risk-Based Corrective Action). This is a standard developed by the American Society for the Testing of Materials (ASTM, 1995). RBCA promotes efficient use of resources by focusing clean-up resources on the most high risk sites using a phased approach to site assessment (this is discussed in more detail in section 4.4). It has been adopted by many States as the most beneficial way to manage the 'UST problem' often after extensive cost/benefit studies have been carried out (e.g., in Iowa and Florida (Groundwater Services Inc., 1995 and 1997)).

Table 4.2 : Comparison of US and UK requirements for prevention of leaks and spills (HSE, 1990; USEPA OSWER, 1995; Environment Agency, 1996b)

Requirements	UK			
	US** New†	Existing	New‡ - SPZI***	New‡ - SPZ II
Leak detection - tanks	Monthly monitoring using: interstitial monitoring; automatic tank gauging; vapour monitoring; groundwater monitoring; statistical inventory reconciliation OR inventory control and tank tightness testing for 10 years after installation (must then monitor monthly)	Monthly monitoring using: interstitial monitoring; automatic tank gauging; vapour monitoring; groundwater monitoring; statistical inventory reconciliation OR inventory control and tank tightness testing for 10 years after adding spill, overflow and corrosion protection - must then use monthly monitoring	Monitoring using (no time interval): interstitial monitoring; automatic tank gauging; vapour monitoring; minimum of four monitoring wells around the dispensing area fitted with vapour detectors and an integrated alarm system to notify Petroleum Officer in alarm conditions	Monitoring using (no time interval): interstitial monitoring; automatic tank gauging; liquid hydrocarbon monitoring of fuel lines; minimum of four monitoring wells around the dispensing area and tank farm fitted with vapour detectors
	Existing sites in SPZ and new sites not in a SPZ			Process of encouragement to follow requirements laid down for SPZs*. Can be emphasised more strongly at times of redevelopment i.e. for new tank installations
Leak detection - pipes	<i>Pressurised piping</i> - automatic shut-off device or flow restrictor or continuous alarm AND annual line testing or monthly monitoring <i>Suction piping</i> - monthly monitoring or line testing every 3 years unless check valve included on each line at the suction pump and piping operates at less than atmospheric pressure and is sloped so contents will drain back into the tank		Positive or suction piping can be used. Line pressure testing to be carried out with product loss monitoring (no time interval). Check valves to be fitted at dispenser base	Monitoring using (no time interval): interstitial monitoring; automatic tank gauging; minimum of four monitoring wells around the tank farm
Spill and overfill protection	Catchment basins and automatic shut-off devices or overflow alarms or ball float valves fitted to all tanks	Must comply by December 1998 - Catchment basins and automatic shut-off devices or overflow alarms or ball float valves fitted to all tanks	Overfill prevention device to be fitted to all tanks. Tanks to be filled from off-set fills aboveground	Overfill prevention device to be fitted to all tanks. Tanks to be filled from off-set fills above or below ground
Corrosion Protection (pipes and tanks)	Double-walled GRP or coated steel & cathodic protection or steel clad with GRP (tanks only)	Must comply by December 1998 - Double-walled FRP or coated steel & cathodic protection or steel clad with FRP (tanks only). Plus options	Double-walled GRP or steel & cathodic protection for tanks with liquid interstitial monitoring Tanks to be coated with epoxy resin inside and out and be	Double-walled GRP or steel with interstitial monitoring. Tanks to be coated with epoxy resin (or equivalent) inside and out and be surrounded by pea gravel or foam

<p><b>Corrosion protection (pipes and tanks) contd.</b></p>		<p>of adding cathodic protection or tank lining or tank lining and cathodic protection.</p>	<p>surrounded by foam. Pipes to be secondarily contained and not be made of steel.</p>	<p>secondarily contained and not be made of steel.</p>	<p>Pipes to be single skin plastic (permeability &lt; 0.2g/m<sup>2</sup>/day) or double walled steel.</p>
<p><b>Registration of tanks</b></p>	<p>All tanks must be registered with the State (environmental protection departments who then pass information on to USEPA). OUST knows how many tanks there are, of what type etc. for the whole of the USA.</p>				
<p><b>Corrective action</b></p>	<p>Confirmed release - must be stopped, contained and reported to the regulatory authority (if release &gt; 25 gallons) within 24 hours. Ensure release does not pose an immediate hazard to human health. Petroleum is removed from UST to prevent further releases. Investigation carried out to find out how far the petroleum has moved and attempt made to recover the product - progress reported to authorities within 20 days of release. Investigate to determine whether release has damaged or might damage the environment - report to the authorities along with a report of how the site will be cleaned up. Based on this, authority will decide if a Corrective Action Plan is needed for further action.</p>				
<p><b>Closure requirements</b></p>	<p>Regulatory authority must be notified 30 days before tank is closed. Site must be investigated to check if contamination is present if it is then corrective action may be needed. The tank may be left in the ground but must be emptied and cleaned and then back-filled with sand. If the tank is removed it must still be emptied and cleaned before removal.</p>				
<p><b>Financial responsibility</b></p>	<p>All tank owners must be able to demonstrate ability to pay for damage costs that could occur if an UST leaked 'per occurrence' \$500,000 to £1 million and 'aggregate coverage' of \$1 million to \$2 million. Amount dependant on value of business and site throughput.</p>				

† Installed after December 22 1988. \* SPZs are only designated for drinking water abstractions and are a non-statutory designation. \*\*US requirements are specifically required by law and apply to retail and 'non-marketer' sites e.g. haulage companies (USEPA, 1988). \*\*\*Agency will oppose new developments in SPZ 1, guidelines are therefore principally for redevelopment. ‡For new sites or new installations at an existing site i.e. redevelopment

### 4.3 RISK ASSESSMENT AND THE RISK MANAGEMENT PROCESS

Risk management has been defined as "the process whereby decisions are made to accept a known or assessed risk and/or the implementation of actions to reduce the consequences or probabilities of occurrence" (Royal Society, 1992: p5). As a process, risk management provides for a structured, systematic and comprehensive analysis of a problem that explicitly acknowledges areas of uncertainty and allows for transparent decision-making (CIRIA, 1995): p1). This last point on the transparency of decision-making is especially important in the regulatory environment where decisions may have to be defended to other regulators, developers, the general public etc.

The process of risk assessment allows for information to be gathered and assessed so informed risk management decisions can be made. Risk assessment is often described as consisting of the following four components (Petts, Cairney & Smith, 1997: p30).

- **Hazard Identification** - what is the source of the pollution, e.g., which contaminants are found at the site? This stage can be carried out within the Source-Pathway-Target model of assessment and will:
  - identify the source of the pollution i.e., the site;
  - identify specific pollutants e.g., petroleum;
  - identify potential targets e.g., a drinking water borehole or groundwater itself;
  - identify environmental media that could be affected e.g., surface water bodies (these could also be termed targets in their own right);
  - identify potential pathways where pollutants could migrate from the site;
  - allow for the development of a conceptual model for the site enabling any further work to be better focused.
  
- **Hazard Assessment** - what could happen to any potential targets? What are the possible exposure pathways and are they credible for a particular situation? In terms of this research, for example, could petroleum leaking from an underground tank reach groundwater and impact on a drinking water abstraction borehole 5km away? A hazard assessment is not a quantified risk estimate but can be used in conjunction with the hazard identification stage to decide on the next course of action, for example (Petts, Cairney & Smith, 1997: p39):
  - levels of contamination are unlikely to present a risk to specific targets judged against relevant generic guidelines and no further action is required; or that

- further site investigation is required (which could involve site-specific risk estimation) in order for observed levels of contamination to be assessed in terms of significance to targets; or that
- levels of contamination are such that remedial action is required.

The outcome of this stage can be used to compare potential risks from a large number of sites, for example, landfill sites or petrol-filling stations. There are many examples of such tools that have been developed for use in several countries, both qualitative and semi-quantitative in nature. They are often termed 'hazard ranking' or 'hazard prioritisation' tools and enable resources to be focused on the most significant risks. They are therefore attractive to politicians as well as practitioners. These type of tools are discussed more fully in section 4.4.

- **Risk Estimation** - what is the probability of a particular hazard scenario occurring and what will be the magnitude of its effects i.e., a prediction of the consequences. This usually involves an 'exposure assessment' where the exposure of the target to the hazard is estimated (i.e., the dose) and an 'effects assessment' where the effect of the exposure on the target is assessed. Detailed information is required for this stage especially if a full quantified risk estimation is needed (semi-quantified estimations are possible). The process is also necessarily site-specific. Tools have also been developed to support this stage of assessment and are often multi-media quantified or semi-quantified models. These types of tool are also discussed in section 4.4.
- **Risk Evaluation** - this stage considers whether the assessed risk is acceptable judged against standards, guidelines and/or site specific objectives. At this stage assumptions made during the assessment must be acknowledged and areas of uncertainty identified.

## **4.4 CURRENT RISK-BASED APPROACHES TO GROUNDWATER PROTECTION**

### **4.4.1 Risk-Based Methods and Models**

The assessment and management of environmental risk has led to the development of a number of models and methodologies to assist in the process. They vary from the qualitative to the more quantitative. Most are not focused on groundwater alone but may consider a range of sources, pathways and targets.

#### *Qualitative or Semi-Quantitative Assessment Methods*

Qualitative or semi-quantitative assessment methods can be useful to assess the risk from a single site but are more often used to compare a range of sites. These kind of assessments can be used to prioritise or rank sites for further investigation, ensuring those sites presenting the

highest risk receive the highest proportion of resources. Users of such methods could include regulatory bodies looking to assess large numbers of apparently similar sites or landowners such as an oil company who wants to assess its land-holdings in terms liabilities (Petts, Cairney & Smith, 1997: p233).

The information requirements for such an assessment need not be high and specific site investigation data is not always necessary. For example, a method developed for use in New South Wales, Australia enabled sites to be 'ranked' by the local authority in terms of contamination (McFarland, 1992). Both human health and environmental risks are considered using factors such as 'proximity to a sensitive environment', 'current and proposed land-use', 'type and nature of contaminants'. A sensitive environment could be a school or an important groundwater resource and would score high as would a chemicals manufacturing plant as a current land-use. As an assessment method it requires considerable expert knowledge to be able to make effective decisions given the subjective nature of the assessment method.

The criteria used to rank or prioritise sites do not even need to be given a numerical score but can be described by 'high', 'medium' or 'low'. Examples of such schemes are those proposed by Henton and Young, (1993); and Wales, Myers and Vogt (1993) as hazard ranking criteria for contaminated sites. This approach is similar to the 'risk matrices' often used to assess industrial risk in terms of human health and safety (Fishwick & Bamber, 1996). A prioritisation scheme developed for former gasworks in France, deliberately uses criteria which will not require site investigation (Costes *et al.*, 1995). Criteria used include site access, present use, depth to water table, groundwater use and presence of population. Criteria that "represent the immediate risk to people" are weighted to score higher.

Some systems can appear to be quite sophisticated. GeoEnviron is a risk-based ranking system developed by the Danish Environmental Protection Agency for point-sources of pollution (it can be adapted for use in other countries) (Pick Everard, 1998). It uses a set of criteria to generate scores based on land-use (human exposure), surface water and groundwater targets. The user must manually choose the appropriate score. As a computer-based tool it offers the user an integrated "environmental information management system" but has a limited help function and requires knowledge of risk assessment etc. on the part of the user to be able to properly use the risk-ranking module of the system.

Some schemes focus on one environmental media only. For example, Shook and Grantham, (1993) developed a technique to prioritise potential sources of groundwater pollution in Idaho, USA. Total rating scores for each source were generated from three components: (i) the regulatory adequacy factor; (ii) the public health risk factor and (iii) the aquifer vulnerability factor. Each was assigned a high, medium or low score based on a set of risk-rating criteria. The regulatory adequacy factor is relatively unusual in such ranking schemes as it is a measure

of “the ability of any regulatory program ... to prevent or remedy groundwater contamination from each source”. The justification given for including such a factor was given as “an adequately regulated source was less likely to contaminate groundwater than a poorly regulated or unregulated source”. This approach is similar in nature to that adopted by the Environment Agency's OPRA (Operator and Pollution Risk Appraisal) programme (Environment Agency, 1997b). The use of OPRA enables 'regulatory effort' to be targeted at high risk processes and has been implemented for IPC regulation. A high level of professional judgement is required to use these kind of decision-making systems successfully.

A similar methodology was developed to assess the risks associated with landfill and to enable decisions to be made about site acquisitions, monitoring activities and new site design (Friz, Piepoli & Zani, 1993). The information required was gathered via a site audit and the subjective nature of the method was acknowledged by the authors but was developed to "guide the expert" so was obviously aimed at the expert user only.

Some methods may appear to be highly numerical and require little expertise on the part of the user. This is not always the case. The Potential Abstraction Risk Index (PARI) hazard ranking system (Keller, Wilson & Neville-Jones, 1989) ranks industrial sites as having low, high or potentially catastrophic risk to drinking water supplies based on a chemical release into a river. A 'PARI rating' can be generated which is used to rank sites and guide, for example, inspection rates at the site. Although relatively simple to calculate, the PARI rating is based on a variety of assumptions that any user should be aware of (e.g. 'acceptable concentration' is based on ingestion by an adult over 24 hours and not a child who would be expected to be more sensitive).

The amount of data required for this level of assessment is not sufficient to carry out a full site-specific quantified risk assessment but does allow a 'phased approach' to site assessment and numerical scores to be assigned allowing site comparison. These methods are sometimes referred to as Tier II assessments whilst Tier I is more of a desk-based study and an initial screening (Tier III would be the site-specific risk assessment). This type of phased approach is demonstrated as a whole by RBCA (ASTM, 1995), RBCA is discussed more fully later in this section. A risk-based staged approach to site assessment can be utilised by industry and provides a flexible yet rigorous and structured approach to the problem. ICI have developed such an approach for soil and groundwater contamination which can support a staged approach to full site investigation and a quantified risk assessment if necessary (Potter, 1992).

Some methods have been developed for use on a national basis for a wide variety of contaminated sites. Probably the most well known is the USEPA Hazard Ranking Scheme (HRS). This scheme is used to rank sites in order to decide whether they should be included on the National Priorities List. Under the Comprehensive Environmental Response,



Compensation, and Liability Act 1980 (CERCLA often referred to as 'Superfund') the USEPA had to establish criteria by which sites could be prioritised for remedial action. The HRS and the National Priorities List was the outcome and was amended in 1986 by the Superfund Amendments and Re-authorisation Act (SARA). After a site has been discovered it is entered into an information system and a preliminary assessment is carried out (USEPA OSWER, 1991). The preliminary assessment is supposed to be a quick assessment and considers the source of the waste, groundwater, surface water, soil exposure and air pathways in terms of the likelihood of release the waste characteristics and possible targets. If the preliminary assessment recommends further investigation a more detailed site investigation is carried out and the site enters the HRS process.

Another example is the Canadian National Classification System for Contaminated Sites (CCME, 1992). This is a screening tool to aid users in categorising sites according to their "current or potential adverse impacts on human health and the environment". It was developed so that assessments could be made on a consistent basis across Canada and uses the source-pathway-target model. Groundwater forms one of the exposure pathways. Although the system of site classification (using a 'scoring method') is quite simple a relatively large amount of site specific data is required to characterise each site accurately (although default scenarios are given). If too many default values are used the site can not be classified. In addition, the user must use a considerable amount of expert judgement in assigning scores, even though guidance is given.

In the UK, a scheme was developed in the 1980's called HALO - Hazard Assessment for Landfill Operations (HMIP, 1988). HALO is considered to be modelled on the USEPA's Hazard Ranking System (Gerrard, 1994). The method consists of six interdependent components such as landfill operations, groundwater pathway, surface water pathway and one independent component (public perception assessment). A series of factors within each component are scored and then weighted according to importance, to give a final site ranking. HALO was never officially published and some authors have criticised the scoring rationale and whether such a scheme could be used in the field (e.g. Petts, Cairney & Smith, 1997: p243). The failure of another methodology, the US Environmental Restoration Priority System (ERPS) was not due to technical difficulties with the system but more to do with lack of stakeholder involvement in its development and political reasons (Jenni, Merkhofer & Williams, 1995).

More recently in the UK, a general prioritisation scheme was published by the Department of the Environment (1995b) to categorise contaminated sites on the basis of future action, which could include a site investigation, site specific risk assessment or site remediation. Sites are assessed in two phases. In phase one, sites are assessed according to proximity to a target based on development (schools, residential areas, agricultural/amenity use, industrial/commercial development), surface water and groundwater. A series of flow-charts

are used and phase one can apparently be undertaken by administrative staff (phase two requires technically qualified personnel). Phase two of the procedure places sites into 'Priority Categories' one to four. For example, a site in priority category 1, "would probably not be suitable for its present use, contaminants are probably or certainly present and likely to have unacceptable impact on targets, and urgent action is needed in the short term". Phase two uses more detailed source and pathway information and a site visit is required. Flow-charts are again used. This prioritisation technique involves many complex decisions, especially in phase two and if not carried out by a person with suitable expertise, could result in a site not being correctly categorised. In addition, although published by the Department of the Environment it is not 'statutory guidance' and the success (or not) of the system has not as yet been reported in the literature.

Site ranking schemes have also been developed for one particular media e.g., groundwater. Such a methodology called DRASTIC was developed by the USEPA (Aller *et al.*, 1987) to assess groundwater vulnerability on a national basis. Seven hydrogeological factors important to assessing groundwater vulnerability (and that should be available) are used: Depth to water table; (net) Recharge; Aquifer media; Soil media; Topography (slope); Impact of the unsaturated zone; and hydraulic Conductivity. A combination of weights and ratings are used to produce a numerical score called the DRASTIC Index. These indices are then mapped onto 'hydrogeologic settings'. The method was prepared to "assist planners, managers and administrators in the task of evaluating the relative vulnerability of areas to groundwater contamination from various sources". It is not a site-specific method but operates at the regional level and it was assumed that the user had only a basic knowledge of hydrogeology. DRASTIC has been adapted for use in other countries (e.g., Bonomi *et al.*, 1994), and used to assess one type of contaminant e.g., pesticide contamination in New Zealand (Close, 1993). It has also been combined with other models (e.g., Ehteshami *et al.*, 1991) and implemented via geographical information systems (GIS) (Merchant, 1994). The DRASTIC methodology forms the basis of the CLASS model (Contaminated Land Assessment System) used by Newcastle City Council to prioritise contaminated land sites for monitoring, site investigation and/or remediation in anticipation of the new contaminated land regime under section 57 of the Environment Act 1995 (Kelly, Lunn & Mackay, 1997). CLASS is also implemented via a GIS system.

In the UK, the DOE have supported the development of a risk-based method to determine the impact of potential or actual land contamination on groundwater and surface water (Department of the Environment, 1994d). It has two main assessment stages: step one is a qualitative assessment, step two is a quantitative impact assessment. Step two is only carried out if an impact is identified at step one. The method is based on the source-pathway-target model and aims to provide "uniformity in methodology, standards and site investigation methods" (Towler

& Young, 1993). The method is not computer-based and is specifically aimed at those with suitable professional experience or qualifications (Department of the Environment, 1994d: p1).

### *Site-Specific and Quantitative Assessment Methods*

The methods described above can be referred to as Tier I methods, and as they become more site-specific and require some site-specific information, Tier II methods. A good desk study and an initial site investigation can provide sufficient data. These methods can be used to prioritise sites for further action and focus resources on those presenting the highest risk to the chosen target (e.g., groundwater, surface water or humans themselves). The next stage of investigation will usually involve a significant increase in the amount of site-specific information that is required and will often use a more quantified approach to site assessment. In the UK, quantified risk assessment (QRA) has traditionally been utilised in the control of industrial risks, for example, at oil refineries and chemical plants (Carter, 1991) and has a longer history than environmentally-based risk assessment (Chapter 2). In the investigation of environmental risk there are several methods available to support a more quantified approach and they are often computer-based. Several of these methods are 'knowledge-based' and are specifically discussed in the next chapter (section 5.3).

The most commonly found group of site-specific models are the 'Fate and Transport' models. In general, they require a high level of user-expertise. Fate and transport models are 'media specific'. There is a second group of models that may incorporate fate and transport methodologies but focus on the 'dose response effect' to assess human exposure for example (Petts, Cairney & Smith, 1997: p251). These are often referred to as 'multi-media' models. Some systems focus on one type of source and look at a limited range of contaminants (e.g. hydrocarbons in the case of API's Decision Support System (DSS) (API, 1996)). Others can deal with multiple sources and contaminants (e.g., RISC-HUMAN, Goldsborough, Smit & Boer, 1995; MEPAS, Droppo Jr *et al.*, 1993) or bring together already accepted models into one system (e.g., Davis *et al.*, 1997).

In the area of groundwater modelling probably the most widely used fate and transport models are MODFLOW (developed by the US Geological Survey) and FLOWPATH (developed by Waterloo Hydrogeologic Software, Canada). The FLOWPATH model, for example, was used by the NRA when designating source protection zones in the UK (Ashley, 1994). Some systems use several fate and transport models together to provide a more flexible system, for example the RUSTIC model provides a framework for risk-based evaluation of groundwater contamination by agricultural pesticides and uses three different models (Varshney, Tim & Anderson, 1993).

It has been noted (Del Vecchio & Haith, 1993) that "management of groundwater pollution risk is facilitated by simple transport and fate models for screening chemicals ... to identify situations most likely to produce groundwater contamination". As models become more sophisticated, (in response to public and regulatory pressures and concerns about inherent uncertainty) there has been a shift away from the 'deterministic' to the 'probabilistic' model in the USA (e.g., Rubin & Cushey, 1994; Hamed, Conte & Bediant, 1995). Examples of probabilistic methods include 'Monte Carlo' simulations and First and Second Order Reliability Methods (FORM and SORM) (Hamed, Bediant & Conte, 1996), and require a considerable level of skill. It has been suggested that an obstacle to using probabilistic techniques is a "general lack of familiarity" (Finley & Paustenbach, 1994). However, the principle of a Monte Carlo simulation, for example, can be integrated into a more user-friendly format. LandSim is one such model. It was designed to allow users (essentially Environment Agency staff) to assess the risk posed by potential landfills to groundwater (Golder Associates, 1995). LandSim provides regulators with an assessment tool to make more consistent decisions (Gronow & Harris, 1996).

The American Petroleum Institute system, the Exposure and Risk Assessment Decision Support System (DSS) (Spence *et al.*, 1993), incorporates fate and transport models as an integral component. It was designed to assist in estimating human exposure and risk from sites contaminated by petroleum hydrocarbons (such as petrol-filling stations) and to develop "negotiable site-specific clean-up levels". It is aimed at the expert risk-assessor but is also "user-friendly" and is similar in that sense to LandSim. The system has physical, chemical and toxicological databases and supports a range of risk assessments. Exposure routes that can be considered include groundwater consumption, dermal uptake, inhalation and ingestion.

One of the earliest developed multi-media screening models to address human exposure was GEOTOX (McKone, 1991). This model screens the potential risks of contaminants released into air, water or soil via inhalation, ingestion or dermal contact. It does not just focus on one type of contaminant like the API system but can of course be used in that way (e.g. Kastenbergh & Yeh, 1993, used GEOTOX to screen several pesticides).

MEPAS (Multimedia Environmental Pollutant Assessment System) developed by the US Department of Energy was designed for use by regulators in assessing the long-term public health issues associated with hazardous site remediations (Droppo Jr *et al.*, 1993). MEPAS is able to integrate risk assessments of radioactive and hazardous substances (carcinogenic and non-carcinogenic) via several exposure routes such as air, surface water and groundwater in order to screen and prioritise sites. It can also be used to prioritise remediation activities in a risk-based way. MEPAS is not a knowledge system but does have some elements of a such a system in that it provides a "shell" through which the user operates the system. The shell

enhances the "user-friendly operation" of the system and aids problem definition and data input (Droppo Jr & Hoopes, 1989). It is, however, still a complex model for an inexperienced user.

MEPAS has recently been incorporated into a system called RAAS (Remediation Action) which is able to carry out further cost-benefit type analyses. MEPAS has also been benchmarked with two other similar models, MMSOILS and RESRAD (both US-based models)(Mills *et al.*, 1997). Although these models were found to be similar, the "environmental processes" they each considered and the assumptions they used differed. These differences could result in "risk predictions differing by orders of magnitude" and the authors emphasised the need to understand what a model is designed to do and what its associated assumptions may mean in terms of the final outcome (Laniak *et al.*, 1997).

Shell International Petroleum developed a model called HESP (Human Exposure to Soil Pollutants) to estimate human exposure to soil contaminants. It was designed to be used as a "Preliminary Exposure Assessment in an early phase of hazard assessment" (Veerkamp, 1994; Veerkamp & Berge, 1994). HESP focuses on three main exposure routes of inhalation, ingestion and dermal absorption for adults and children living in a house on a contaminated site but is focused on soil contamination. HESP is used by the IOP in their Code of Practice on the investigation and "mitigation" of petroleum land contamination (IOP, 1993: p36 & 53) as an example of a human exposure assessment and shows how land use is important. However, the HESP program is not a Windows™-based program and requires a high level of user expertise in order for it to be used in an effective manner.

The system RISC-HUMAN (version 2.0) (Goldsborough, Smit & Boer, 1995) is a Dutch system that uses the fate and transport model CSOIL and can be used to assess site-specific human health risks from soil contamination (RISC stands for Risk Identification of Soil Contamination). RISC-HUMAN is actually three prototype systems that have been added together to form the final system and consists of RISC-HUMAN, RISC-TRANSPORT and RISC-URGENCY. RISC-TRANSPORT calculates transport of organic contaminants in groundwater (Smit, Goldsborough & Boven, 1995) and RISC-URGENCY is a ranking system for possibly contaminated former industrial sites (Goldsborough & Smit, 1995). The system is Windows™-based and user-friendly but is based on Dutch guidance and standards. The model it is based on, CSOIL, was developed for use in deriving human-toxicological intervention values under the Dutch Soil Clean-up Guidelines (Berg, 1993). However, CSOIL has been criticised, with differences in calculated concentrations using CSOIL and actual measurements which resulted in the model being adjusted (Huijsmans & Wezenbeek, 1995). This emphasises the necessity for full model verification especially when incorporated into a decision-support system and awareness on the part of the user of the concepts behind any system they use.

A USEPA system, Risk\*Assistant is able to look at any contaminated site and estimate human exposure from a variety of pathways and provide a site-specific human health risk assessment. Exposure from contaminants in air, water (including groundwater) soil and biota are considered. It also contains databases of information (the USEPA IRIS database, for example) and international soil guidelines (the Dutch Intervention values, for example). There are a wide variety of human exposure models, some may focus exclusively on a particular media, for example the US Electric Power Research Institute model AERAM - Air Emissions Risk Assessment Model (Seigneur, 1994). Others may focus on certain contaminants e.g. carcinogenic contaminants.

SoilRisk is an integrated carcinogenic risk model for low levels of organic contaminants in soil that can be used as a screening model (Labiencic, Dzombak & Siegrist, 1996c). Although not so flexible as other models that carry out multimedia assessments (e.g., MEPAS, MULTIMED, Root & McLaughlin, 1993; Salhotra *et al.*, 1993) it is not so data intensive or 'computationally demanding'. Soil Risk can be used to produce probability distribution functions of 'risk' and can evaluate the variability in risk when sites across a region are remediated to a single contaminant concentration (i.e. clean-up standards) (Batchelor & Araganth, 1998). It has shown that in general, for highly degradable contaminants such as benzene, a relatively small degree of 'regional risk variability' is found. However, with highly mobile or persistent contaminants such as trichloroethylene, a large degree of variability is found (Labiencic, Dzombak & Siegrist, 1996b). SoilRisk has been incorporated into a methodology that allows the establishment of "compound-specific concentration-based uniform soil remediation goals for meeting a target cancer risk ... and to estimate the variability in risk due to variable site properties" (Labiencic, Dzombak & Siegrist, 1996a).

A model discussed briefly above, RBCA, is perhaps indicative of a new type of model. It supports phased or tiered approach to risk assessment which protects human health and the environment at all tiers (Rounds & Johnson, 1995). RBCA (as it stands at the time of writing) is an ASTM standard for site investigation and remediation at petroleum contaminated sites (ASTM, 1995). Remediation is often driven by regulatory standards which can not take account of site-specific variability, resulting in 'over or under-remediation'. Remediation using 'best available technology' may remediate beyond what would be protective of human health and the environment therefore wasting resources. In addition, the technology may not have been sufficiently verified and may be distrusted. RBCA is said to address these problems by providing a risk-based but site-specific framework (Rounds & Johnson, 1995; Vits *et al.*, 1995). The key features of RBCA are that it provides:

- a framework for risk-based regulations
- for a consistent decision-making process
- a tiered approach which is increasingly site-specific

- a resource effective process as it focuses resources to the most high risk sites

Working through the tiers decreases uncertainty but increases data requirements. This may imply an increase in remediation cost but as uncertainty has decreased a more site-specific remediation plan can be carried out which can be associated with a lower final cost.

Tier I is a screening level, with the RBCA process supporting the development of a series of 'risk-based screening levels (RBSLs) for a series of likely exposure scenarios (other screening methods could be used, HESP is given by Vits *et al.*, (1995) as an example). Tier II RBCA sets out a process that allows determination of site-specific remediation target levels (SSTLs) which will almost certainly be less conservative than the RBSLs. If the Tier II corrective action plan is not acceptable then a Tier III assessment can be carried out using a site-specific model such as API's Decision Support System. RBCA as a process is also to be applied in the future at sites where other types of chemical contamination are found i.e. not just petroleum contaminated sites (Begley, 1996).

Although many methods have been developed to support risk-based decisions and several that support site prioritisations there are some disadvantages and deficiencies that can be identified in current practice.

#### **4.4.2 Deficiencies of Existing Risk Management Methods**

The use of risk-based decision-making as a management approach has several advantages:

- it is a systematic and logical process
- it provides for consistent decision-making
- it allows efficient use of resources (financial or personnel) by focusing on the higher risk sites
- it allows for a 'tiered' or phased approach to solving the problem
- it allows risk management actions to be prioritised

As discussed there are many methods and models available to assist in the management of groundwater pollution and the assessment of environmental risk in general. The feeling that their use may be overzealous, particularly if computer-based, has been stated, however, such models should be viewed as tools to *assist* the user (e.g., Narasimhan, 1995).

The use of fate and transport models often presents particular problems to the user: (i) they can be time-consuming to use, for example, Ashley (1994) states that four weeks was needed to fully characterise a specific site using MODFLOW or FLOWPATH; and (ii) the user must be aware of the underlying conceptual model that the system is based on and how actual field

conditions may differ. This information is not often explicit and transparent to an inexperienced user.

Methods are often underpinned by a series of assumptions which may not be clearly stated and the implication of using such assumptions may not be clear to the inexperienced user. For example, Kastenbergh and Yeh (1993) have stated that the following assumptions are common in most human exposure assessments:

- uniform distribution in time for consumption of drinking water, aquatic organisms, animal and vegetable products
- local products are consumed
- synergistic or antagonistic effects due to exposure to one or more 'pollutant' (pesticides in Kastenbergh's case) are not considered
- drinking water consumption consists of half surface water and half groundwater

In addition to the technical problems of using such systems there may also be physical issues such as poor user-interface design that can leave a potentially useful system, unused and unwanted by the people it was designed for. If the concepts of user-centred system design are utilised this need not be the case. The development of the RISC-HUMAN system was relatively unusual in that a user analysis was carried out and the system modified accordingly (e.g., a detailed knowledge-base was added as a user help system) (Goldsborough, Smit & Boer, 1995).

Risk-based decision-making has only relatively recently entered into statutory control and environmental management in the UK, the new contaminated land regime is still not yet enacted fully. In other countries with a longer history of this type of decision-making, the USA in particular, there has been a tendency to go down the fully quantitative route of health risk assessments with concerns about its efficacy and effectiveness (e.g., Wildavsky, 1995).

The risk management process is based on information: collection, evaluation and dissemination. The type of information that is critical to the process for each site may differ. Table 4.3 gives an indication of the types and possible multiple sources of information that may be required when carrying out an investigation into a site's history and background, prior to a full-scale field investigation. Experience is required to know what type of information is required and where it may be obtained, this puts the inexperienced 'risk-assessor' at an immediate disadvantage and could lead to inconsistent decision-making.

There are also a wide variety of institutions and bodies making such decisions and at several different levels. Table 4.4 shows some examples. These bodies may be termed 'official' in the sense that many have statutory duties to perform. An inexperienced risk-assessor may be



confronted with a vast amount of information, and some of it may be conflicting, making consistent robust decision-making difficult (even for the experienced person).

**Table 4.3:** Sources of information and types of information that may be utilised during investigation of a site in the UK (e.g. RPS Consultants Ltd, 1994)

Source of Information	Location/form of Information	Type of Information
Site owner or site operator	Detailed site plans, deeds for the land, site records	Details of site features, photographs of site, site operational details
Local Authority - County Council/Metropolitan authorities, Borough Council offices	Department of Planning records and personnel  Department of Environmental Health - records and personnel Fire Service e.g. Petroleum Officer	Historical records of land use at the site, previous owners, previous investigations  Previous land uses, public health incidents at site Site operational details
Central Government	Department of the Environment, Transport & Regions - records and personnel	Current policy on site investigations
National governmental bodies	Environment Agency (including HMIP, NRA and WRA records) - records and personnel English Nature - records and personnel	Details of previous investigations, previous owners, previous landuses, location of water abstraction points Information on status of any nearby SSSI's or nature reserves
Universities/research bodies	Library research, interviews with academics	Current thinking on site investigation methods, geology, hydrogeology, site remediation techniques
Local people	Interviews with ex-workers or local residents	Information that may not be recorded anywhere else - e.g., spill location
Others	British Geological Survey	Geological/hydrogeological maps for area, soil maps

In addition to the 'official' decision-making bodies, Table 4.5 gives some examples of other types of body who also have an impact on environmental decision-making and may have very different agendas compared to those in Table 4.4. and who may pressurise, for example a regulatory body such as the Environment Agency and require justification for the decisions they make. As a Agency worker making risk-based decisions (or trying to) information and views from these kinds of bodies must also be taken into account in order to ensure fully informed decisions.

**Table 4.4:** Levels of environmental decision-making and examples of bodies making those decisions (adapted from Brown *et al.*, 1995: p59)

<b>Level of Decision-Making</b>	<b>Decision-Making Body</b>
<i>International</i>	United Nations (UN) e.g. Earth Summit, Rio de Janeiro, 1992 OECD International Panel on Climate Control
<i>European</i>	European Commission European Court of Justice European Environment Agency
<i>National</i>	Environment Agency for England & Wales Scottish Environmental Protection Agency Ministry for Agriculture, Fisheries and Food Department of Environment, Transport & Regions Countryside Commission for England & Wales English Nature Forestry Commission English Heritage
<i>Regional/Local</i>	Elected councillors (including Parish Councils) Local Authority Planning Departments National Park Boards Local Authority Environmental Health Departments

**Table 4.5:** Examples of those bodies who may seek to have an input to the environmental decision-making of those listed in Table 4.4

<b>Level of Decision-Makers</b>	<b>Bodies Seeking Input</b>
<i>International</i>	Multi-national companies World-Wide Fund for Nature
<i>European</i>	European-based companies
<i>National</i>	Royal Commission on Environmental Pollution English Heritage The National Trust National Farmers Union Country Landowners Association Council for the Protection of Rural England Greenpeace Friends of the Earth British Trust for Conservation Volunteers Farming & Wildlife Advisory Group Ramblers Association Waste management companies Nationally-based companies
<i>Regional/Local</i>	Individuals Landowners/Landlords Local action groups

In summary, the disadvantages of using a risk-based approach to decision-making particularly in a regulatory environment include:

- complex decisions must be made across a wide variety of disciplines
- availability of relevant experts may be restricted

- decisions often have to be made quickly and with variable amount and quality of information (decisions are performed in a state of uncertainty without complete knowledge)
- the concept of risk is relatively new to many within the regulatory environment

There are a large number of methods that can be used to support risk-based decision-making that also try and address some of the disadvantages listed above. However, almost without exception they fail in one or more respects - usually they require quite a high level of experience in the user (professional judgement) and if computer-based often a high level of familiarity with computers. In addition, models developed to date are rarely 'user-focused', they are not designed with the potential user in mind, their requirements and limitations. One of the major objectives of this research has been to show that one particular type of computer-based models called expert or knowledge-based systems can go some way to promote the advantages and reduce the disadvantages of using a risk-based approach to decision-making. These type of systems can support the user without replacing their input and enable less experienced people to make decisions in a risk-based way, supported by these type of systems as screening or prioritisation models. The next chapter describes in more detail what knowledge systems are, how they are different from more conventional systems, the types of problem they are suitable for and the process of developing such a system.

## CHAPTER 5

### 5 KNOWLEDGE AND KNOWLEDGE SYSTEMS

#### 5.1 INTRODUCTION

##### 5.1.1 Definitions

Knowledge systems form a branch of artificial intelligence, which has been defined as "the study of mental faculties through the use of computational models" (Charniak & McDermott, 1985: p6). In the 1960's, workers in the field of artificial intelligence tried to develop computer programs that were 'intelligent' and could behave as a human would when problem-solving. They noted that given a problem to solve, even an unfamiliar one, people could make progress towards completing their task apparently because intelligence consists of a relatively small set of subject-independent problem-solving methods (Davis, 1986).

Early knowledge-based programs were developed based on this observation. However, although these first programs provided an insight into human intelligence, when faced with complex real-life problems (as opposed to artificial problems) they performed unsuccessfully. The reason for this was recognised by Edward Feigenbaum in the mid 1970's. He realised that the actual problem-solving ability of a program, its 'intelligence', comes from the knowledge which it has, not the way in which it solves the problem. This change of approach led to the rapid expansion of the branch of artificial intelligence that came to be called expert or knowledge-based systems.

The first key text to discuss expert systems defined an expert system as (Hayes-Roth, Waterman & Lenat, 1983):

"A computer system that achieves high levels of performance in task areas that, for human beings, require years of special education and training"

The key point in this definition is 'achieves high performance in task areas'. An expert system is a special-purpose computer program that operates in a specific problem or task area. These systems utilise human expertise and apply it to complex problems.

Terminology in this field can be confusing. The term 'expert system' was originally used in the 1970's and early 80's. However, the term 'knowledge-based system' and recently 'knowledge system' have been used, often synonymously. A knowledge-based system is a computer program where the problem-specific knowledge is separated out from the general problem-solving knowledge (Waterman, 1986: p18). If that problem-specific knowledge comprises 'expert knowledge' that can be applied to real-life problems, then the system can also be termed an 'expert system'. There is a difference between a knowledge-based system and an expert

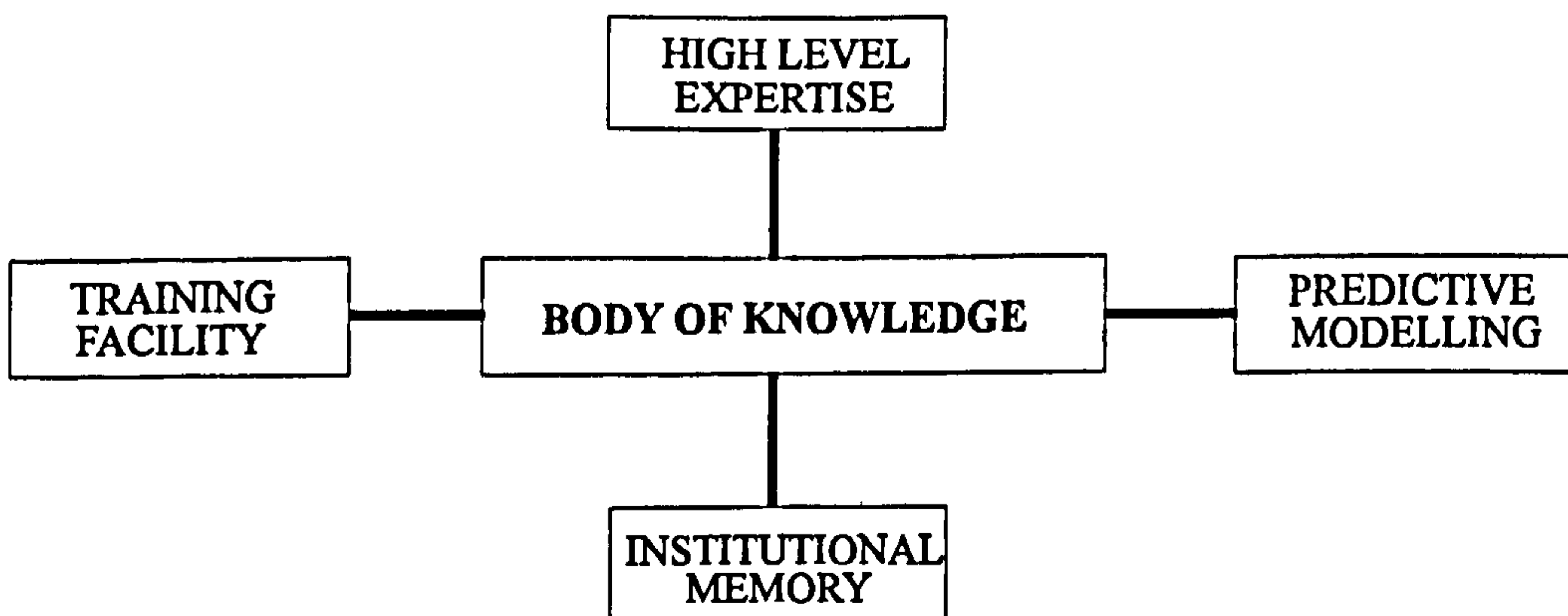
system but it is only of real importance in discussions regarding artificial intelligence research and not the applied use of such systems.

As discussed by Stefik (1995: p296) the term 'expert system' has other disadvantages. Although the best expert systems can outperform human experts in a narrow area, they have less 'breadth and flexibility' in their operation when compared to human experts. For example, a system designed to give advice on a person's ideal weight for their height would not recognise that a data input of 76 for 'height in metres' is clearly not correct, but if a doctor were carrying out the same assessment they would be able to recognise an incorrect answer. This can lead to confusion and arguments about the nature of expertise. The term 'knowledge-based system' removes this confusion by focusing attention on the knowledge the system has, not whether that knowledge is 'expertise'. The term knowledge system is 'shorthand' for knowledge-based system and is used throughout this thesis.

### *Knowledge System Characteristics*

Knowledge systems assist non-expert or less experienced personnel in solving complex problems that they may not be capable of solving fully or effectively at that point in time due to lack of knowledge and/or experience. Such systems do not replace human expertise but enhance it (Crowe & Mutch, 1994) by assisting a non-expert to use data/information to solve a problem in a similar way as an expert would, given the same data/information.

The most important part of a knowledge system is the body of knowledge it holds. A distinguishing feature of knowledge systems compared to other computer-based programs is that this knowledge is explicit and accessible. Figure 5.1 illustrates the key features of a knowledge system.



**Figure 5.1:** Features of a knowledge system (Waterman, 1986: p6)

A knowledge system can (Hayes-Roth, 1984a; Waterman, 1986: p6):

- Solve difficult problems in the manner of an expert, which is often more effective than using a human expert direct (in resource terms) and allow non-experts to formulate an expert decision.
- Use heuristic knowledge or 'rules of thumb' when problem solving.
- Use natural language (as opposed to program code, for example) when interacting with users.
- Allow the user to evaluate changes in the data and how a different outcome might be obtained (predictive modelling power).
- Provide an 'institutional memory'; the system is a compilation of knowledge and a permanent record of peoples' expertise.
- Provide a 'training facility'; the system contains 'high level knowledge' and it can explain the reasoning processes behind a decision and justify the conclusions reached.

The knowledge system approach has been used in a broad variety of problem domains such as medical diagnosis (PUFF, MYCIN), chemical structure elucidation (DENDRAL) and mineral prospecting (PROSPECTOR). Table 5.1 indicates areas where historically this technology has been applied (Waterman, 1986: p40).

**Table 5.1:** Historical application areas for knowledge systems

Application Areas	
Agriculture	Manufacturing
Chemistry	Mathematics
Computer Systems	Medicine
Electronics	Meteorology
Engineering	Military Science
Geology	Physics
Information Management	Process Control
Law	Space Technology

Knowledge systems have been developed for a wide variety of problem areas from finance to retail packaging (Hayes-Roth & Jacobstein, 1994). A survey undertaken by Durkin (1993 and 1996) showed that approximately 2,500 developed systems had been identified across a wide variety of application areas that included agriculture, education, engineering, medicine, manufacturing, environment and business. There has been a dramatic increase in the numbers of systems being developed since the 1980's.

A survey carried out in 1993 (Lewis, 1994) focused on business sector, and found that systems had been developed and were planned in many different business sectors. For example, the business service sector (35 systems built, 60 planned) manufacturing (19 systems built, 29 planned) and the chemicals sector (8 systems built, 28 planned).

Systems have been developed beyond the research prototype and are being used in the 'real world', an example being the DHSS Performance Analyst used by the British National Health

Service to evaluate medical care. These evaluations used to take six human experts on average two hours but can now be done on average in nine minutes. In the finance sector, American Express uses a system to authorise credit transactions which it is estimated saved it \$27 million in 1986 due to more effective decision-making (Feigenbaum, McCorduck & Nii, 1988: p111). Knowledge systems and associated knowledge processing would seem to have a successful commercial future (Hayes-Roth & Jacobstein, 1994) and is now an "effective tool for addressing real-world problems" (Durkin, 1996).

The use of a knowledge-based approach to problem solving has been applied only relatively recently to the environmental field but is developing rapidly. Systems have been built for use in regulatory support, site assessment and remediation, risk assessment, groundwater contaminant modelling and water resource management (Crowe & McClymont, 1992). The types of systems developed and the reasons for their application are discussed in section 5.3.

Knowledge systems can also be categorised into types independent of the application area (Table 5.2). Historically, systems were classified into one category but this is becoming an outdated and restrictive view. Systems often exhibit elements of several different categories listed in Table 5.2, for example, a diagnostic system may exhibit elements of planning or prediction (Kidd, 1987).

**Table 5.2:** Types of knowledge system and the types of problems they address (Hayes-Roth, Waterman & Lenat, 1983; Waterman, 1986: p33)

Type of Knowledge System	Problem Addressed
Interpretation	Inferring situation descriptions from sensor data
Prediction	Inferring likely consequences of given situations
Diagnosis	Inferring system malfunctions
Design	Configuring objects under constraint
Planning	Designing actions
Monitoring	Comparing observations to expected outcomes
Debugging	Prescribing remedies for malfunctions
Repair	Mending things using prescribed remedies
Instruction	Diagnosing, debugging and repairing student behaviour
Control	Governing overall system behaviour

### 5.1.2 Knowledge and Expertise

A true knowledge system does not just hold pure facts, it also holds the encoded reasoning and decision-making processes of the expert: i.e. how situations are interpreted. Much of this type of knowledge is heuristic or 'rules of thumb' (Waterman, 1986: p17) and is difficult to put into a guidance note or a text book. A knowledge system can use models of cause and effect based on a set of rules and these rules can be formed from 'heuristic' knowledge in addition to 'facts'. Such a system is based on the body of knowledge it holds, which is used to make decisions to solve problems. To fully understand what knowledge systems are and what they can do, the

questions of what is knowledge and expertise and what constitutes an expert, need to be considered.

### *Knowledge and Information Characteristics*

Cognitive psychology identifies that expertise which comes from the knowledge an expert has, is not held in one mass and that learning is a segmented, iterative process (Anderson, 1995: chapter 9). The definition of what is expertise and knowledge is not simple.

Knowledge has been defined formally in several different ways, for example, declarative knowledge and procedural knowledge. Broadbent (1989) discusses the need to represent declarative and procedural knowledge when thinking about any process (not necessarily a knowledge system). Declarative knowledge is described as "general facts about the world": e.g., the strata are Permo Triassic Sandstone. Procedural knowledge, however, is the knowledge of "what actions to take under what conditions". Anderson (1995: p236) also describes declarative knowledge as "knowledge about facts and things" and procedural knowledge as "knowledge of how to perform various cognitive activities". It is procedural knowledge that is used for problem solving.

Hayes-Roth, (1984b) presents declarative and procedural knowledge as three dimensions of knowledge:

- scope - ranging from the general and widely applicable to the specific and narrowly applicable
- purpose - ranging from the descriptive to the prescriptive purpose
- validity - ranging from certain to uncertain

These dimensions can also be represented graphically and are shown in Figure 5.2.

La France (1986) has developed a "Forms of Knowledge dimension" that recognises that expert knowledge is complex and is difficult to elicit in the context of developing a knowledge system. Her five Forms of Knowledge are perhaps a more practical way to describe expert knowledge when developing a knowledge system:

*Layouts* - this type of knowledge constitutes the expert's 'map' of the problem area; the basic classifications and organisational structure of the problem area.

*Stories* - this type of knowledge is represented by typical examples and case studies that the expert has collected whilst working in the area.

*Scripts* - this type of knowledge describes the procedural knowledge the expert uses; what to do and when to do it.



*Metaphors* - this type of knowledge is presented as alternative methods or analogies the expert may use when solving a problem or describing it to someone else.

*Rules of thumb* - this type of knowledge is the expert's heuristic knowledge of a problem area and allows the expert to deal with a variety of different situations and different problems.

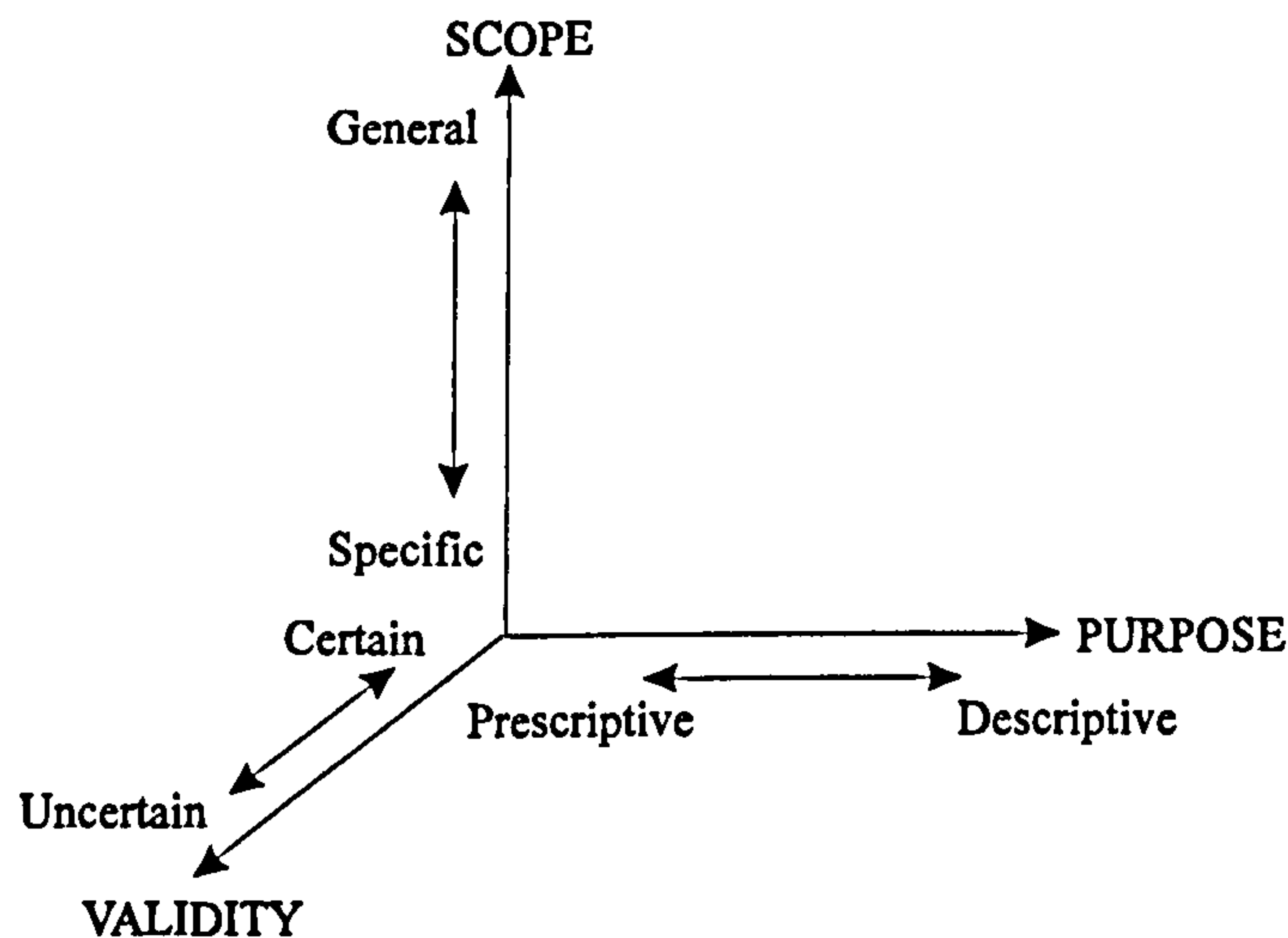


Figure 5.2: The three dimensions of knowledge (Hayes-Roth, 1984b)

The kind of knowledge used by the expert when solving a problem and how that information is presented to them is critical to knowledge system development. Because 'knowledge' can be categorised in many ways, the process of identifying what is required for system development can be difficult. The type of knowledge required and utilised by the expert must be capable of being represented within a knowledge system if that system is to be successful (or even built at all). Clarke *et al.*, (1992) divided this knowledge into three basic categories:

- (i) Existing knowledge - legislation, published information - data
- (ii) Acquired knowledge - elicited from domain experts - skills
- (iii) New knowledge - research

The nature and quality of the knowledge is highly important. The quality of knowledge utilised by lay-people, experts and potential system users can vary enormously (Clarke *et al.*, 1992). Knowledge from text books in particular should be good quality and reliable; it has been used and tested, possibly over many years and is generally accepted as 'fact' (however, acceptance does not always denote good quality). Knowledge gained from research papers could be termed the most 'unreliable' as it may be new, and untested but could provide very useful information so should be included. Knowledge from people themselves may be as reliable and as good a quality as books but not always. This type of knowledge, often heuristic knowledge, is difficult to test even though it may be very adequate. An expert is constantly 'upgrading' his knowledge base with new knowledge, and this may alter parts of his reasoning and decision-making strategies.

An important question is whether the system has got to reason with only incomplete information or a great deal of uncertainty. Enough information must be acquired from the various sources to enable the knowledge-base to be sufficient to solve the problem the system was designed for (and no more) (Clarke *et al.*, 1992). The system will not be successful if there is insufficient knowledge for the problem to be assessed in the first place, so the problem definition is crucial (this is discussed further in section 5.2.2).

### *Experts and the Nature of Expertise*

Human reasoning strategies and decision-making or problem solving strategies have been studied for several decades, (a key text being Newell & Simon, 1972). It is now firmly a part of cognitive psychology (e.g. Anderson, 1995: chapter 9). However, the terms expert and expertise can still be interpreted in a variety of ways.

The way we acquire a certain skill can be broken down into three distinct stages (Anderson, 1995: p273):

- Cognitive stage
  - where the declarative knowledge is learnt, the 'facts' are relevant to the skill
- Associative stage
  - errors in the initial understanding are detected and eliminated
  - connections among the various elements required for successful problem-solving are strengthened
- Autonomous stage
  - the procedure becomes more automated and rapid
  - speed and accuracy increase

An expert in a particular skill or problem area has passed through all these stages. Experts are "distinguished by the quality and quantity of knowledge they possess; they know more and what they know makes them more efficient and effective." (Hayes-Roth, 1984b).

Three different types of experts have been identified (Shadbolt & Burton, 1995):

- (i) *Academic* - they regard their domain as being logically organised, generalisations about the laws and behaviour within the domain are important. Theoretical understanding is of great importance. They may feel they must present a consistent 'story' but that story will be the correct one. They believe that the problem can be solved by applying the correct theory.
- (ii) *Practitioner* - they solve problems in their domain on a day-to-day level, specific problems and specific events are important. They need to see the problem solved

within the constraints they must work under. Theoretical understanding is not that important and they may operate at the heuristic level.

(iii) *Samurai* - they are only interested in performance, practice may be the only training and responses are often automatic.

In reality an expert may express any or all of these behaviour 'types', and the differences are represented along several dimensions, such as: the outcome of their problem solving; the environment they work in; the knowledge they possess; their status; their sources of information and the nature of their training.

Humans use knowledge to decide what to do and how best to do it: i.e. they reason to make decisions and both reasoning and decision-making are high-level cognitive skills (Johnson-Laird & Shafir, 1994). Humans are not so good at some types of reasoning, for example, 'counterfactual reasoning', such as would Y have occurred if X had not. Humans can also find selecting the 'right' information for the task and thinking through the consequences of complex interactions difficult (Kidd, 1987). Experts are also subject to bias in their judgements, which can be exacerbated during the knowledge elicitation process (Cleaves, 1987). The subject of expert bias has been well documented, particularly in the risk management literature (e.g. Tversky & Kahneman, 1974; Slovic, Fischhoff & Lichtenstein, 1980; Kahneman & Tversky, 1982; Slovic, Fischhoff & Lichtenstein, 1982; Otway & von Winterfeldt, 1992).

As there are differences in experts there are also differences in the levels of expertise. There are differences between how experts and non-experts perform, experts having acquired the necessary procedural knowledge relevant to the problem (Wagner & Sternberg, 1986) and having reached the 'autonomous stage' of learning (Anderson, 1995: p274). Hoffman *et al.*, (1995) attempted to describe various 'levels of expertise' basing them on terminology used by the mediaeval craft 'guilds' (Table 5.3). In the context of this research some analogous expertise descriptions can be suggested (Table 5.4).

As Hart (1986) described, experts and their expertise can be used in a variety of ways familiar to us all:

*Expert as an information provider* - experts hold a significant amount of detailed information about a particular area that is readily available to them. You can ask them questions and discuss cases and they can explain their answers in terms a non-expert can understand.

*Expert as a problem solver* - by using the knowledge they have an expert can solve problems and identify what information would be needed to make their solution more accurate.

*Expert as an explainer* - an answer to a problem is not always that useful to a less experienced person. The 'site is categorised as severity code 1' is not that useful if you are

not sure what 'severity code 1' is. An expert can explain their reasoning process of how they came to the answer and so aid the non-expert in developing their own expertise - in this case understanding the reason why a site is given a severity code 1 and what the latter implies.

**Table 5.3:** Mediaeval 'Guild' terminology and expertise (Hoffman *et al.*, 1995).

	Description of Expertise
Naivette	One who is totally ignorant of domain
Novice	Someone who is new to the domain - a probationer, some minimal exposure to the domain
Initiate	Someone who has been through the initiation ceremony - a novice who has just begun introductory instruction
Apprentice	Someone who is learning - a student undergoing a programme of instruction beyond the introductory level. Traditionally, the apprentice is immersed in the domain by living with and assisting someone at a higher level
Journeyman	A person who can perform a days labour unsupervised, although working under orders. An experienced and reliable worker, or one who has achieved a level of competence
Expert	A distinguished or brilliant journeyman - highly regarded by peers, whose judgement is accurate and reliable, whose performance shows skill and economy of effort and who can deal effectively with 'rare' cases. One who has special skills or knowledge derived from extensive experience
Master	Any journeyman or expert who is qualified to teach those at a lower level. Traditionally a master is one of an elite group of experts whose judgements set regulations and standards. A master may be an expert who is regarded as 'the' expert by other experts, or the 'real' expert

**Table 5.4:** Levels of expertise in the domain of groundwater protection

	Description of Expertise
Naivette	A small child who has not yet started school
Novice	GCSE level student - sciences/geography
Initiate	A level student - sciences/geology/geography
Apprentice	HND/BSc student - geology, hydrogeology, environmental sciences or a new starter as a hydrogeologist etc.
Journeyman	Someone who has worked as a hydrogeologist for example, for a year or two - still supervised by a senior colleague but able to work independently, able to apply knowledge learnt as a student
Expert	Someone who has many years of experience in groundwater protection, guides the work of more junior colleagues, is well-known in the field and whose views are well respected
Master	Someone who gives keynote papers at international conferences on groundwater, sits on the committees that draw up latest guidelines and standards for the protection of groundwater. They are called upon by other experts to discuss unusual problems and decide on future direction of research. They are well-known in the field of groundwater protection in other countries and other fields as an expert

During an interaction with an expert, they will often take on the role of information provider, problem solver and explainer in one session. In summary, a human expert can be described as someone who (Glaser & Chi, 1988):

- excels in their own domain and possess a large amount of domain knowledge
- is able to perceive patterns in their own domain
- is faster than non-experts at performing tasks in their domain
- can solve problems with less error than non-experts
- is able to identify a reasoning strategy as incorrect, faster than a non-expert
- is able to represent a problem at the 'principal' rather than the superficial level
- spends time understanding a problem before moving into the analysis phase

An expert is efficient, effective and knows their limitations (Hart, 1986). The identification and co-operation of a suitable expert to knowledge system development is a key stage and is discussed in more detail in Chapter 6, section 6.1.3.

### 5.1.3 Knowledge System Structure and Knowledge Representation

The basic structure of a knowledge system is shown in Figure 5.3. The knowledge base holds the problem-specific knowledge, often in the form of rules. The inference engine is the part of the program that is able to select and apply that information contained in the knowledge base to the problem under investigation (Davis, 1986).

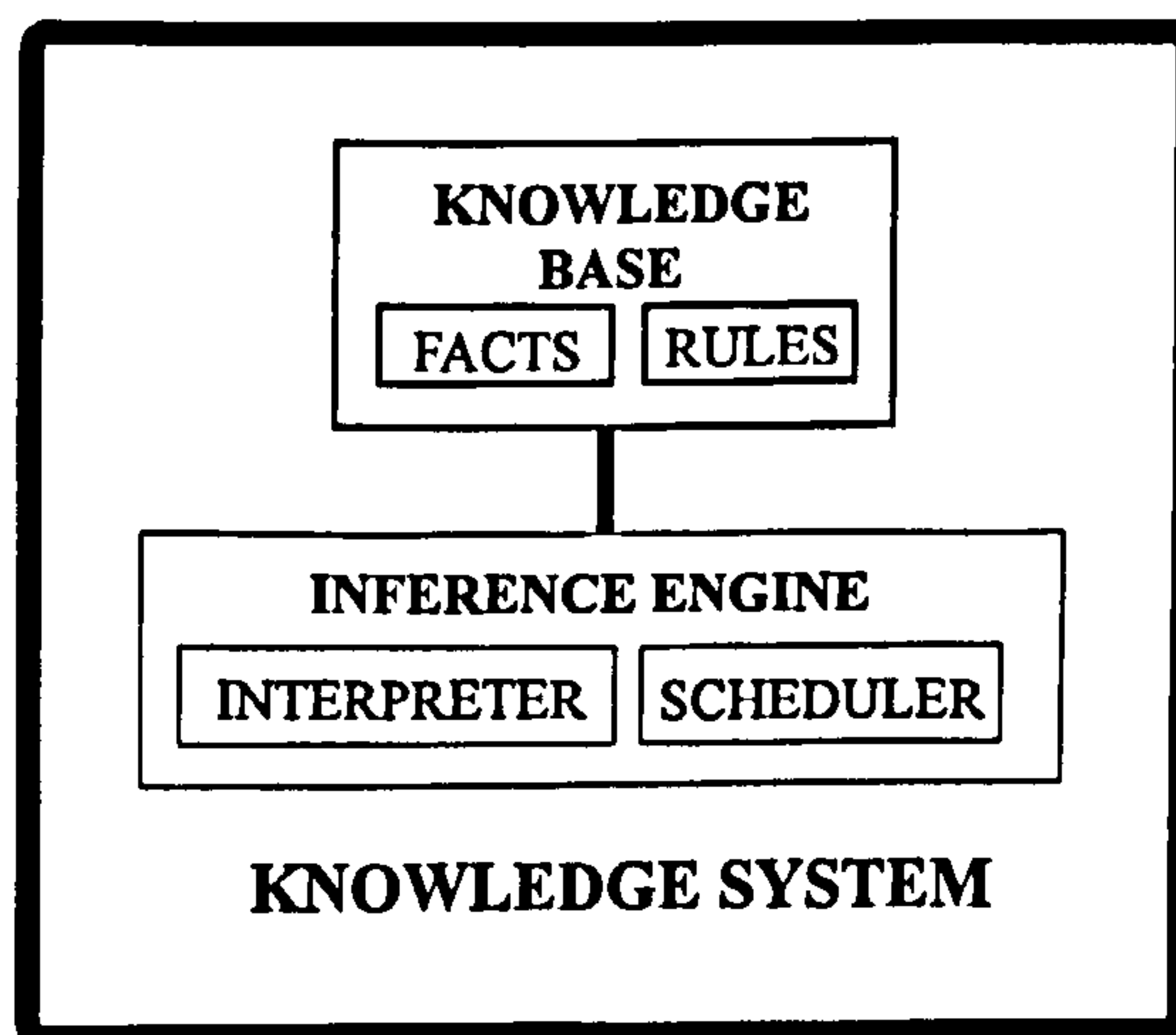


Figure 5.3: The structure of a knowledge system (adapted from Waterman, 1986: p19).

Knowledge contained in a knowledge system must be represented so that the computer can manipulate it. This representation can be by rules, logic representation, semantic nets or frames. The most common way to represent knowledge as part of a knowledge system is by IF-THEN rules or *condition* and *action* rules (Waterman, 1986: p23; Mockler, 1989: p20). The rule representation is relatively simple, modular (each rule is separate and can be changed

individually) and can represent procedural as well as declarative knowledge (Siegel, 1986: p8). Rule examples are shown below:

IF animal has hair	
AND animal produces milk	<i>Declarative</i>
THEN animal is a mammal	
IF spill is of petroleum	
AND is on a major aquifer	<i>Procedural</i>
THEN remediation action necessary	

The use of if-then rules is not exclusive to knowledge systems, conventional programs can also use this type of representation. The structure provided by such rules is also used to some extent in fault tree analysis and event tree analysis in relation to hazard assessment.

In a rule-based knowledge system these rules can be used by the inference engine in two different ways called 'forward chaining' and 'backward chaining' (Davis, 1986; Waterman, 1986: p66). Forward chaining describes reasoning from observations to conclusions. In the example above, if the spill is of petroleum and it is on a major aquifer then remediation is necessary. Backward chaining starts with a hypothesis and moves backwards through the rules to observations, that may or may not support that hypothesis i.e., a goal is required, 'Remediation is necessary' and if the rules 'spill is petroleum' and 'major aquifer' are true then the hypothesis is true and remediation is necessary. Backward and forward chaining are similar in process to 'fault and event trees' used extensively in the health and safety field, especially in the investigation of accidents or process failures.

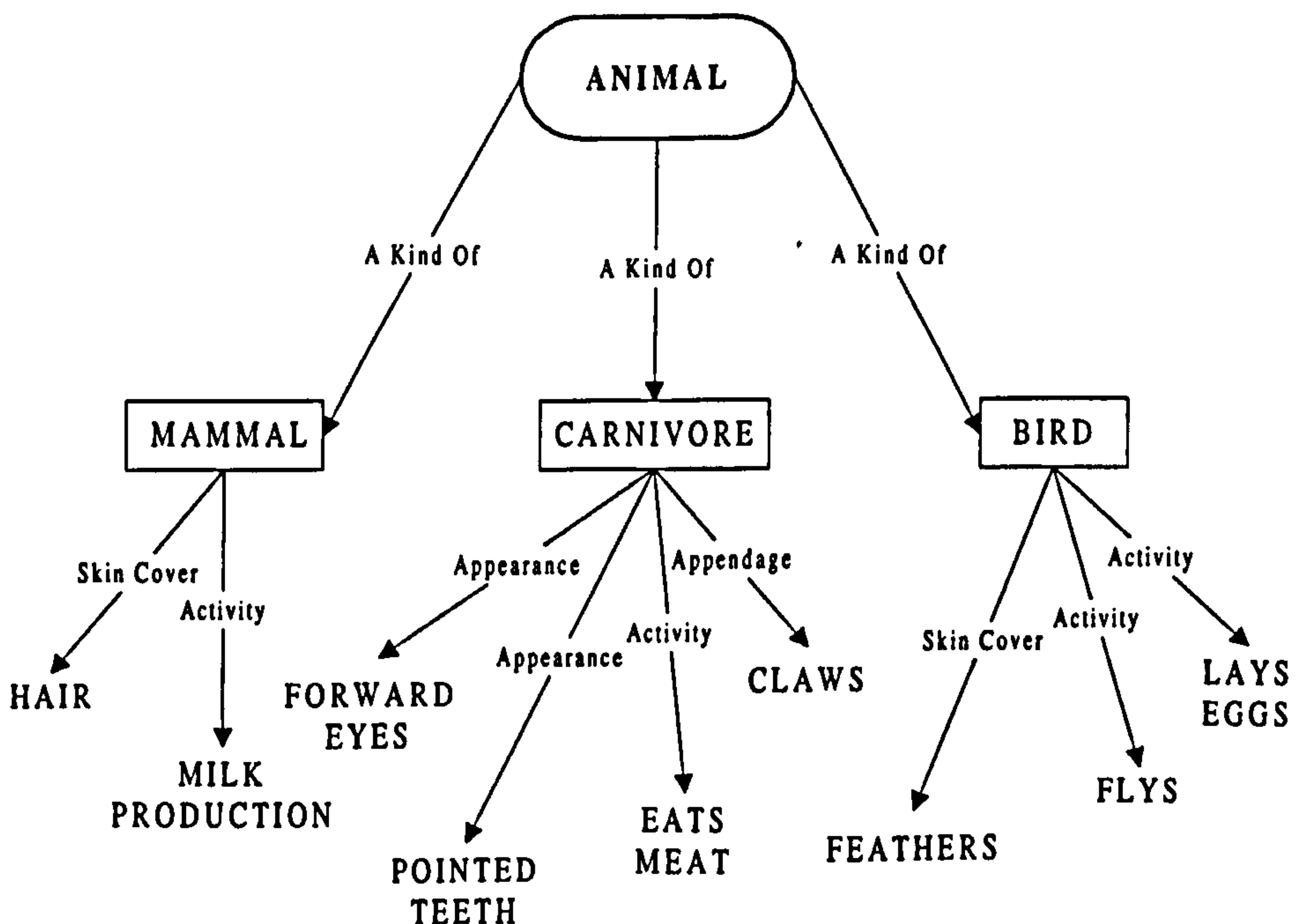


Figure 5.4: An example of a semantic net (Siegel, 1986: p6)

Another way of representing knowledge in a knowledge system is by using *semantic nets*. Semantic nets show relationships (links) between concepts (also called nodes). The method is visual and can be easily understood by users and experts (Clarke *et al.*, 1992). A diagrammatic example is shown in Figure 5.4.

A third type of representation uses *frames*. Using a frame representation allows information to be held together on related concepts. An example is shown in Figure 5.5. The information is structured into a frame, where the properties of an object are held in slots of the frame. A frame can hold procedural knowledge as well as declarative knowledge and therefore they are more appropriate for complex domains (Siegel, 1986: p8). These types of systems are also called object-oriented systems and could be said to model the way humans really reason about a problem. As frame-based systems are often more complex than rule-based systems they are not so widely used in PC applications (Mockler, 1989: p27).

MAMMAL		CARNIVORE		BIRD	
A KIND OF ANIMAL		A KIND OF ANIMAL		A KIND OF ANIMAL	
Skin Cover	Hair	Appearance	Forward Eyes	Skin Cover	Feathers
Activity	Produces Milk	Pointed Teeth		Activities	Flys
		Appendage	Claws		Lays Eggs
		Activities	Eats Meat		

Figure 5.5: An example of a frame representation (Siegel, 1986: p7)

Mathematical or logical representations using constants and variables to give definitive statements can also be used to represent knowledge e.g., ON(ROOF ANTENNA) = the antenna is on the roof. This method of knowledge representation however, has been shown to be difficult for domain experts and users to follow when more complex information is represented this way (Biondo, 1990).

## 5.2 VALUE OF A KNOWLEDGE-BASED APPROACH

### 5.2.1 Knowledge Systems and Conventional Programs - why use a knowledge-based approach?

Conventional computer programs are good at solving routine, repetitive problems; they manipulate data such as numerical models. Knowledge systems solve problems that are normally restricted to experienced personnel/experts: i.e. tasks that require experience, judgement and the use of heuristic knowledge. A knowledge system can prompt the user for information and data, it can assist in filling in the 'gaps' and help with the interpretation of the results (Crowe & Mutch, 1994). Knowledge systems can manipulate knowledge rather than just processing it as data (Waterman, 1986: p24).

To distinguish a knowledge system from an ordinary computer program it must have certain characteristics (Brachman *et al.*, 1983):

- *Expertise* - the system must achieve an expert performance and be able to solve problems a human would and be skilful in that problem solving. Human experts usually solve problems more quickly than those less experienced. They use 'short cuts' and 'tricks of the trade'.
- *Robustness* - i.e. be able to reason from first principles when its knowledge base is not complete - humans do this regularly and easily.
- *Depth* - the system must be able to deal with complex problem domains and be able to use complex rules.
- *Self Knowledge* - the system must be able to examine its own reasoning and explain how it reached a conclusion by using its inference chains (the explanation facility of a working system) .
- *Symbolic Reasoning* - Humans do not usually use complicated mathematics to solve problems, they think of problems in terms of concepts and replace the numbers with symbols. A knowledge system must be able to manipulate symbols, so how knowledge is represented in the system is important.

There are three basic reasons for using a knowledge system as opposed to a conventional system (Hayes-Roth & Jacobstein, 1994):

- to improve the reasoning of the system
- to increase the flexibility of the system
- to increase the human-like qualities of the system

For a system to be successful, it must be of some use or benefit (Basden, 1994). Of those systems already in use in the industrial and commercial arena, an extended list of benefits have been identified (Hayes-Roth & Jacobstein, 1994):

- increased speed of performing tasks
- increased quality
- reduced errors
- reduced costs
- reduced training time
- retention of knowledge
- improved customer service



System design has often focused on the technological features, and the ease of use, of a system. As long as these requirements were satisfied (sometimes only the former being fully satisfied) a successful system would be the outcome (Basden, 1994). However, in reality there is a need to identify the benefits of using any knowledge system which Basden has classified as:

- (i) feature benefits
- (ii) task benefits
- (iii) role benefits

Benefits resulting from features of the system such as the speed at which it works, the consistency of the answers it gives, the quality of the 'help' system, can be described as feature benefits. Task benefits can be described by the tasks the system supports and the support it gives to the user within their organisation. The latter might include 'improved response times', 'improved training', or 'better understanding of the problem'.

The role the users have in using the system and why they carry out those tasks supported by the system, are important when assessing role benefits. Role benefits might be 'increased productivity' or 'better customer service'. They arise from the effect the system has on the roles the user fulfils by carrying out the tasks supported by the system. Basden argues it is the role benefits (not feature or task benefits) that will indicate the success or failure of a system in the field (Figure 5.6).

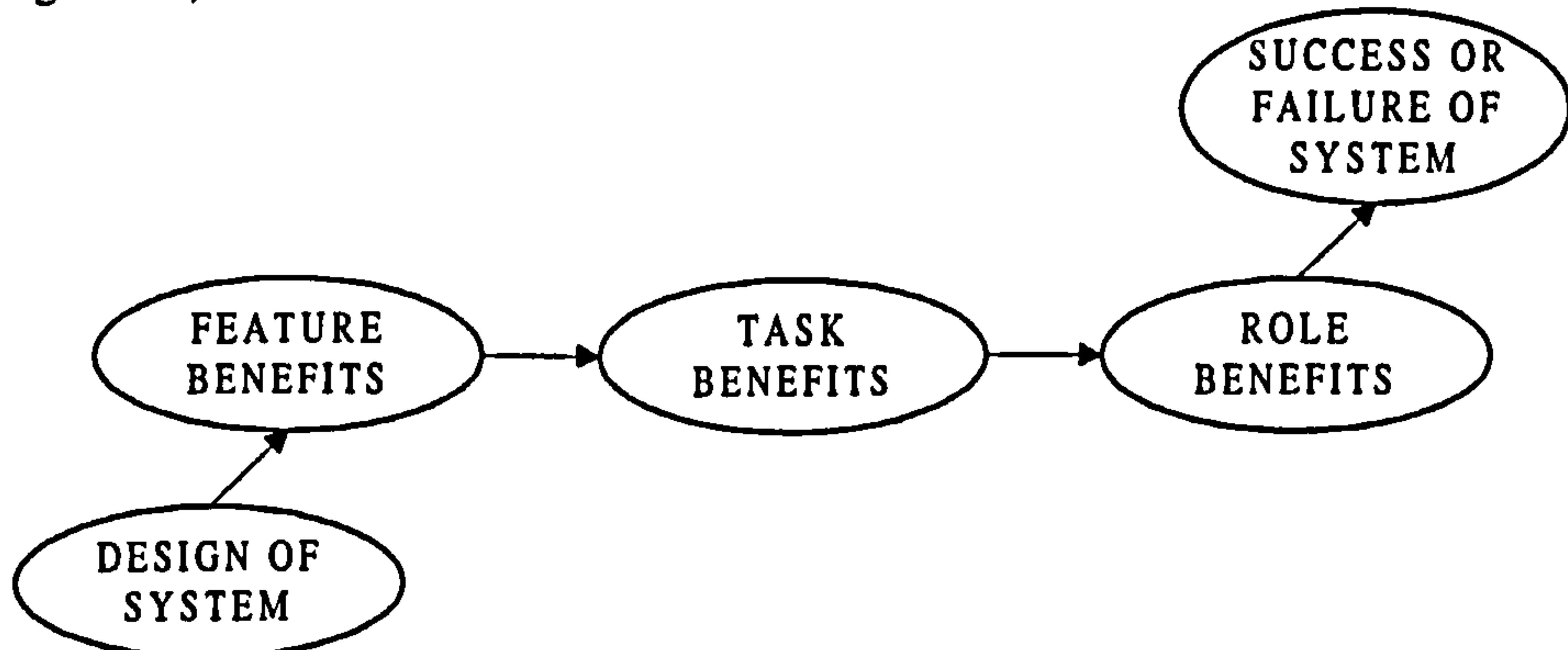


Figure 5.6: Three levels of benefit (Basden, 1994)

### 5.2.2 Is Knowledge System Development Possible, Justified and Appropriate?

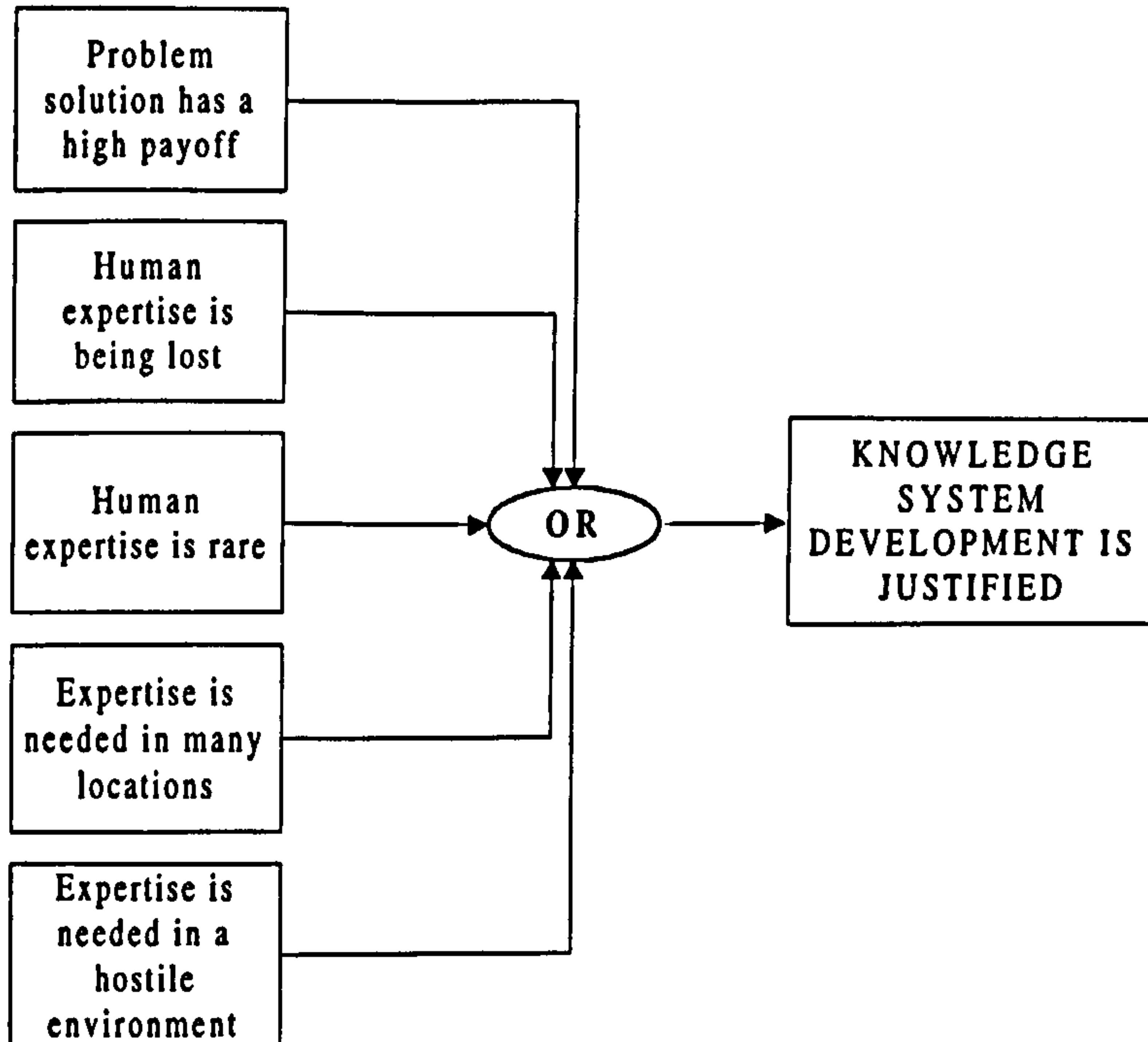
Even if the benefits of system development can be identified, there are three fundamental questions to be addressed (Waterman, 1986: p127):

- (i) Is system development possible?
- (ii) Is system development justified?
- (iii) Is system development appropriate?

Not all problem areas are suitable for knowledge system development and application, however, the following problem characteristics are frequently cited as necessary for development to be possible (Waterman, 1986; Hushon, 1987; Hushon, 1989a; Crowe, 1994):

- the problem area is not too difficult and is relatively well understood;
- the problem occurs often (so the developmental costs of a system can be justified);
- a solution to the problem requires expert judgement and interpretation as well as factual knowledge;
- a human expert exists who can articulate their methods and experts agree on the solutions;
- there should be a sufficient number of case studies to enable any knowledge system developed to be verified;
- problem solution requires consistency of response even when data input varies in quantity and quality, and
- the use of a knowledge-based approach must be more effective than alternative methods.

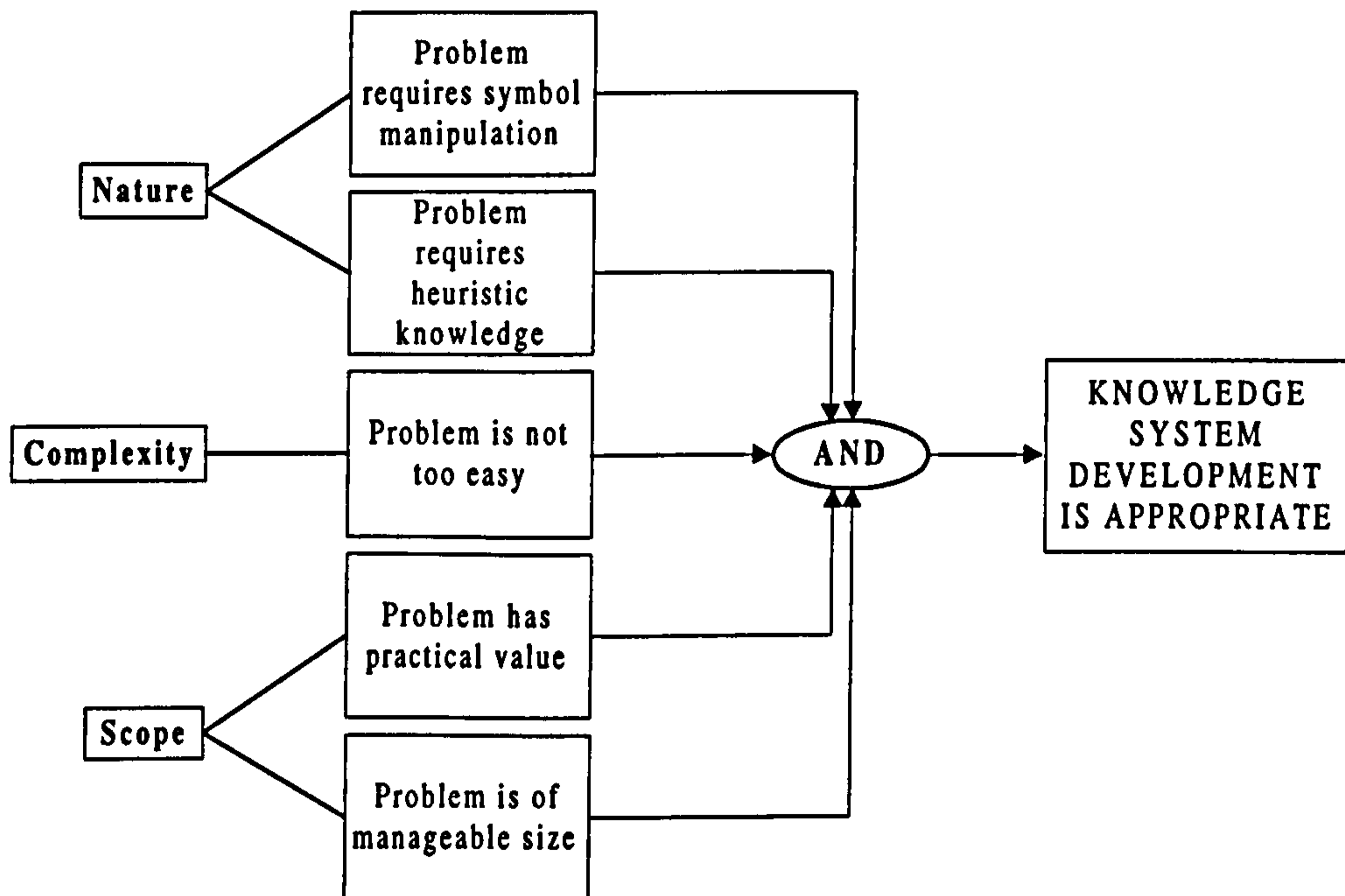
Even if a knowledge system can be built for a problem area and the problem is suitable, can the development of such a system be justified? Waterman, (1986: p130) lists some justifications for developing a knowledge system and these are shown in Figure 5.7.



**Figure 5.7:** Justification for knowledge system development (Waterman, 1986: p130)

The development of a knowledge system could be justified by any one of the factors listed in Figure 5.7. System development may be possible and justified but it must also be appropriate.

Waterman (1986: p 132) describes three factors that determine whether knowledge system development would be appropriate, they are the nature of the problem, its complexity and its scope. Figure 5.8 shows how these factors are related to problem characteristics.



**Figure 5.8:** Problem characteristics that make knowledge system development appropriate (Waterman, 1986: p132)

The nature of a problem is important when deciding whether knowledge system development would be appropriate. Human experts do not generally solve problems by using equations or other mathematical representations, rather they use concepts to represent a problem and manipulate concepts. These problem concepts in turn can be thought of as symbols which can then be manipulated by a knowledge system (symbolic reasoning). So the nature of a problem appropriate for knowledge system development must be such that to solve the problem involves manipulation of concepts or symbols and a solution is not represented by mathematical reasoning alone. A second facet of the nature of a problem that would make knowledge system development appropriate is the use of heuristic knowledge in solving the problem (rules of thumb). If the problem can be adequately solved mathematically or if it requires an algorithm (a procedure guaranteed to produce the correct solution every time) then a knowledge-based approach to solving that type of problem would not be appropriate.

The second key development factor is the complexity of the problem - this is a difficult concept to represent in words but the problem must not be too 'easy'. It must encompass a problem area that takes a human several years of study to be considered an 'expert'. The problem of learning the 12-times table would not be appropriate for knowledge system development as it is not complex enough (although development would be possible).

The final factor to appropriate development is the scope of the problem, which Waterman considers to be critical to system success. The problem area must be 'manageable': i.e., the scope of the problem must be narrow enough to make practical system development possible. For example, a problem area that encompassed the assessment of all contaminated sites in the UK (possibly tens of thousands) on the basis of risk would not be manageable. In making the problem manageable however, its solution must still remain of practical use. Reducing a problem area down to the assessment of sites in Loughborough contaminated with boron, may not make solution of the problem using a knowledge system of any practical use.

Several authors have identified other areas of importance to system development, such as who will be the system users (e.g., Berry, 1994) what are their needs (e.g., Clarke *et al.*, 1992) and who are the experts in the field (e.g., Neale, 1988). These other areas are discussed in more detail in Chapter 6, section 6.1.

In deciding whether a knowledge-based approach to problem-solving is the correct one, the problem area must be identified carefully and checks made so that before the system is fully developed there will be answers to the questions posed above. Some workers have attempted to do this in a formal manner (e.g. Laufmann, De Vaney & Whiting, 1990). Laufmann *et al* set out an evaluation methodology for assessing potential knowledge system domains based on a scoring system. A range of issues such as "How available is the necessary domain knowledge?" and "Will the knowledge system meet a real need?" are rated and on completion of all questions provides 'an overall measure of potential success'. This type of approach is valuable when developing a commercially oriented system and Laufmann *et al* admit that many of the questions can really only be answered fully once a system has been released into the field.

The point is that before any actual system development commences, the problem area must be considered against the key questions: i.e. is development possible, justified and appropriate? The identification of Agency activities (described in chapter 4, section 4.2) such as 'responding to a petrol spill' and the 'prioritisation of such activities', suggest that a knowledge-based approach could be appropriate but this statement must be verified. This is discussed more fully in Chapter 6, section 6.1 and Chapter 7, section 7.1.

## **5.3 KNOWLEDGE SYSTEMS AND GROUNDWATER APPLICATIONS**

### **5.3.1 Knowledge Systems - History of Use in the Environmental Field**

Knowledge systems have been built to solve many different kinds of problems, but (as identified in Table 5.2) their basic activities have traditionally been grouped into several problem solving categories, such as, interpretation, prediction, design, planning, monitoring, control, diagnosis and instruction (Hayes-Roth, Waterman & Lenat, 1983). A wide range of

systems have now been developed in these categories within the field of environmental management (Warwick, Mumford & Norton, 1993). However, initially (from the mid 1980's) environmental knowledge systems were relatively limited and this was possibly due to the type of hardware that was then required to build them (the shell environment had not yet been fully developed) and the difficulties of representing certain types of environmental decision-making (Hushon, 1987). A possible reason for the relatively late emergence of 'environmental knowledge systems' may be "the science for dealing with environmental problems is not well understood and there are few absolutely agreed upon methods" (Borman, 1989).

By 1987, Hushon could identify 21 "expert systems for environmental problems". These included the GEOTOX system which enables waste disposal sites to be hazard ranked in terms of risk to surface or groundwater (Anon, 1985) and the RPI site assessment system which follows the procedures used by the USEPA HRS but for site permeability and groundwater flow only (Law, Zimmie & Chapman, 1986). By 1989 this had increased to nearly 70 systems and was predicted to reach 80 by 1990 (Hushon, 1989a). More recently there have been several systems developed as risk assessment tools, such as the USEPA's Risk\*Assistant, which assesses human health risks posed by hazardous waste (Hushon, 1989a) and the Dutch RISC-HUMAN system (Goldsborough, Smit & Boer, 1995). Systems relevant to environmental risk management such as RISC-HUMAN (in particular those that consider groundwater) have been discussed in more detail in section 5.3.2 but some examples of other environmentally-based knowledge systems include:

- ECOZONE, a knowledge system for training planners in the environmental impacts of agriculture (Edwards-Jones & Gough, 1994), HyperAIA, an integrated system for environmental impact assessment (Antunes & Camara, 1992), EIA in engineering projects (Mercer, 1995), road projects (Lelievre & Serodes, 1995) and other environmental impact systems reviewed by Geraghty (1993)
- A knowledge system developed to guide the selection of waste treatment alternatives in the US pulp and paper industry - this system includes economic, technical, social and political aspects (Wei & Weber, 1996), MIN-CYANIDE for cyanide waste minimisation in electroplating works (Huang, Sundar & Fan, 1991), WMEP-Advisor for the whole plating process (Luo & Huang, 1997)
- The Landfill Design Advisor (LDA) designed for the "preliminary design of landfills in developing countries" - includes modules on site suitability, leachate and gas management, environmental monitoring and control (Basri & Stentiford, 1995) and the Landfill Restoration Plan Advisor (LRPA) (Basri, 1998)
- A knowledge system for the preliminary planning of municipal solid waste management systems (in Canada) - includes sections on waste generation and composting forecasts, technology evaluation, facility cost and location (Barlshen & Baetz, 1996)

- Knowledge systems for selection of industrial and municipal wastewater treatment processes (Yang & Kao, 1996), plant design and operation (Ladiges & Kayser, 1994; AEA Technology, 1997)
- A knowledge system for assessing the criteria in EC Water Quality Directives and subsequent compliance of a surface water body for subsequent use as, for example, drinking water (Wishart, Lumbers & Griffiths, 1990)
- An environmental information system that acts as a decision-support system to facilitate the development and implementation of environmental policy in the area of water resources (quantity and quality) (Fraser & Hodgson, 1995)
- ERexpert system that can assist in the development of an appropriate emergency response following an accidental chemical spill (Zhu & Stillman, 1995a; Zhu & Stillman, 1995b) and the ARSEN project which can model natural hazards such as avalanches (Buisson & Cligniez, 1995)

Environmental problem solving is suited to knowledge system development but due to certain problem characteristics the field itself has had to expand further. Avouris, (1995) suggested that environmental problem solving can be characterised as follows:

- it tends to be multidisciplinary in nature - there will not be a single expert who can solve the problem - this leads to co-operative problem solving
- conflict will often be a feature; with so many involved differences will arise, therefore negotiation and consensus building should be a part of environmental decision making
- the physical environment is hard to model, it is dynamic in nature
- heuristic knowledge may be commonly used which is hard to generalise, experts may use a wide variety of methodologies to solve problems depending on their backgrounds
- the spatial element of a problem can be global or of a narrow geographical area - difficulties in combining information
- available information is often imprecise, uncertain or even wrong

Many of these characteristics are of course not limited to the environmental field and several of these problems could utilise a knowledge-based approach e.g. dealing with imprecise data.

### **5.3.2 Current Applications - With a Focus on Groundwater**

Crowe, (1994) suggests that the specific characteristics of groundwater pollution that are conducive to a knowledge-based approach, are :

- 'natural systems' exhibit complex behaviour and considerable variability to which decisions are generally applied with sparse or incomplete data
- some groundwater pollution problems occur regularly but the type, quantity and quality of information that must be used to make a decision is variable

- related investigations often utilise knowledge from other fields - geology, biology, toxicology etc.
- some relevant hydrogeological research is directly relevant but is beyond the expertise of most hydrogeologists and engineers
- problem solutions must be based on scientific principles and regulatory constraints

These points apply to the decision-making environment of the Environment Agency with regard to UK groundwater protection: i.e. decision-making in a regulatory environment (Chapter 8, section 8.1). Decisions are made with high levels of uncertainty with regard to the information the decision-maker has available. Those making the decisions are drawn from a wide variety of disciplines. Most are not expert contaminant hydrogeologists or expert risk assessors, although most are technically trained. All decisions are made within the regulatory context of, for example, time limitations, financial resource limitations etc.

The types of risk-based model developed to date in the area of site contamination tend to be focused on Tier II and Tier III assessments (Chapter 4, section 4.4). There are examples of models that are multi-media in approach and others that focus on one medium such as groundwater (and may be highly site-specific). The use of knowledge systems in this area is relatively recent. Crowe & McClymont, (1992) and Crowe (1994) reviewed those systems that were available for site assessment and remediation (with a focus on groundwater pollution) recording 22 systems (some of which were at the proposal stage). Due to the nature of computer-based systems in general (not just knowledge systems) the type of systems developed have tended to be Tier II and III and are often highly sophisticated.

Some of the more relevant systems to contaminated land and groundwater issues are briefly discussed below, highlighting who the system was aimed at, what each system is capable of and any limitations.

#### *Site prioritisation and hazard ranking tools*

The Defense Priority Model (DPM) was developed to enable the US Department of Defense to rank sites for remediation purposes and by 1991 had been used on more than 500 sites (Hushon & Read, 1991). The DPM was developed from the HARM and HARM II systems (Hazard Assessment Risk Model) developed for the US Air Force in 1984. It was designed to give relative potential risks to human health and the environment from sites containing hazardous materials to enable those sites to be ranked for remedial action (Hushon, 1989b). It is based on a source-pathway-target model and includes pathways for surface water, groundwater, air and soil. It includes non-human targets (which not all models do) but the human targets are more highly weighted. The DPM is one of the earliest and most successful applications of a knowledge system to an environmental risk-based problem.

The HMA Software tool is a German system that incorporates knowledge-based modules along with more traditional databases etc. (Groh & Pahl, 1993). It aims to guide the "semi-professional" user in identifying and evaluating potentially contaminated sites. Part of the system provides support for site investigations including sampling regimes for air, surface water, groundwater and soil. HMA is specifically aimed at the Local Authority decision-maker faced with the management of a large number of contaminated sites, and not at the highly sophisticated and experienced user (Selke, 1993).

### *Risk assessment tools*

The model AERIS (An Aid for Evaluating the Redevelopment of Industrial Sites) was prepared for use by Environment Canada (Robins & Clark, 1993). It considers on-site human health risks of older contamination. As the model focuses 'on-site' it does not take account of some exposure pathways/scenarios 'off-site' (Calabrese & Kostecki, 1992). AERIS was developed to determine clean-up criteria for soils at derelict industrial sites by estimating the human health risk from the various contaminants on the site. The main objective of the system was to ensure that assessment and application of clean-up criteria were consistently applied (Crowe, 1994). In the UK the forthcoming CLEA model will have a similar aim. It is not known how successful AERIS has been and it has proved difficult to determine the extent of its current use.

Risk\*Assistant is also a multi-media model and was developed for use by the USEPA, to carry out its own risk assessments at hazardous waste sites and assess those carried out by outside contractors. The system evaluates the number of people who may be exposed to a contaminant, concentration exposure and how the exposure occurred. These are then combined with toxicity and carcinogenic information to arrive at a health risk. The system was designed to increase the quality of assessments and improve consistency (Crowe, 1994). The system is also more 'contaminant' oriented than site oriented and there is no provision for assessing site clean-up levels (Calabrese & Kostecki, 1992).

Knowledge systems have also been used as part of an overall risk management strategy. An example is that used in the Paris area as an 'aquifer protection strategy' (d'Arras & Suzanne, 1993). This strategy is similar to the use of source protection zones in England and Wales and is catchment based. As part of the overall strategy there is in place a 'pollution control strategy' which uses a range of tools to: (i) determine the pollution risk of an incident; (ii) assess the impact of the incident; and (iii) resolve the incident. Some of these tools are knowledge-based: for example, the CASTOR module of the pollution control strategy allows the drinking water distribution system to be re-configured after a major incident and is a crisis management tool. Specific knowledge systems have been integrated with more traditional models and policy decisions to form a risk management strategy.



A more ambitious system is the IRIMS (Ispra Risk Management Support) system which aims to "facilitate the assessment of alternative policies and strategies for the management of industrial risk" and is aimed at the regulatory sector (Fedra, 1989). It considers the production, transport and storage of hazardous chemicals and not just their disposal. It includes a range of contaminant transport models including a groundwater model (FEFLOW).

#### *Groundwater contaminant modelling - fate and transport models*

OASIS is a system that can act as a "toolbox" for groundwater contaminant modelling and aquifer clean-up (Newell, Haasbeek & Bediant, 1990). It utilises a 'hypertext' user-interface so is easy for the user to navigate through the system. It has been developed as a decision-support system and although knowledge-based, the authors state it is not a traditional 'expert system', although it has been reviewed as such (Crowe & McClymont, 1992; Crowe, 1994). It supports a knowledgeable user in defining a problem and makes available a suite of models and tools that the user can utilise to solve their problem. The toolbox includes databases of, for example, chemicals and useful references. OASIS also provides the user with access to models such as BIOPLUME (Norris *et al.*, 1994: p191), DRASTIC (Aller *et al.*, 1987) and Expert ROKEY (McClymont & Schwartz, 1991).

Expert ROKEY is itself composed of several modules with a knowledge system called EXPAR guiding the user and giving assistance and advice when required (McClymont & Schwartz, 1991). The system allows users to estimate values for the physical, biological and chemical parameters controlling groundwater flow. The modular approach allows experienced users to use Expert ROKEY without having to go through all the advice screens etc. but they are easily available to a non-expert user. The modular structure also allows the system as a whole to be updated and changed easily, providing a level of flexibility which a single 'non-modular' system does not have.

Systems have also been developed to assess a particular class of contaminants, for example pesticides and their potential risk to groundwater. EXPRES (Expert System for Pesticide Regulatory Evaluations and Simulations) is such a system. It was developed for use by the Federal Pesticide Agency in Ottawa, Canada (Crowe, 1995) and is aimed at those not expert in the theory of pesticide transport in soils. It is a screening tool to evaluate potential for pesticides to pollute groundwater (Crowe & Mutch, 1994). It also assists with the interpretation of results and is specifically aimed at regulatory personnel. EXPRES uses several pesticide assessment models (such as PRZM, LEACHM) and contains rules to select an appropriate model and estimate model parameters. In that sense it is similar to the more recently developed Risk-Based Remediation model (RBR) (Davis *et al.*, 1997). The RBR package uses already well-established fate and transport models (such as MODFLOW) to develop site-specific clean-up measures. The difference between the models is that EXPRES supports a less-experienced

person in selecting the correct model for the task under consideration, whereas the RBR package is a method of integrating several models but without being explicitly knowledge-based. An in-depth knowledge of site investigation and remediation is still required to use the RBR package.

In the UK, a knowledge system has been developed called "Physiochemical Evaluation: The Environment" to assist MAFF with the assessment of pesticide safety by demonstrating how pesticides move through the soil and into plants (Nicholls, 1996). This system has also been incorporated into the NRA system (now the Environment Agency) called POPPIE which is a pesticide risk assessment tool for catchment areas.

EXPRES has been incorporated into the commercial decision support system called RAISON™, which has been developed by the Canadian National Water Research Institute (NWRI Software, 1997). RAISON™ (Regional Analysis by Intelligent Systems ON microcomputers) is a Windows-based modular system that can act as an environmental information system. It provides a framework so that other information systems can be accessed and environmental modelling methodologies can be integrated (Crowe & Booty, 1995). It is a highly visual system allowing GIS information to be incorporated. RAISON™ was first developed in 1986 (as a lake acidification model, (Swayne *et al.*, 1992)) but is now being offered for sale as a commercial software product that will run on a PC (Pentium processor and Windows 95 required). It can be used by the expert and non-expert user as the user can decide the 'depth' to which they want to use the system. Barriers to its use may be the cost and that it is focused on the Canadian environment (although it could be adapted for use elsewhere).

Some systems are highly specific, for example HYDRISK (Heynisch *et al.*, 1994) considers contaminated sites as a whole (i.e. not just one type of contaminant) and addresses the risk assessment of the subsurface of contaminated sites. It evaluates hydrogeological properties and chemical criteria in relation to chemical transport and suggests suitable remedial actions and future land uses. The system assesses the probability that the groundwater will become polluted to such an extent that land use or groundwater use would present a human health hazard. HYDRISK is only suitable once detailed site investigations have been carried out, as extensive geological and hydrogeological data is important for a risk assessment using HYDRISK. HYDRISK is supported by a GIS and this allows maps of potential risk to groundwater from contamination to be presented to the user. The system is able to pinpoint specific areas of high risk that enable more efficient use of remediation resources. Although this system is knowledge-based it requires a high data input on the part of the user and is aimed at the knowledgeable user.

A slightly different approach is that taken by De Leo, Del Furia & Guariso (1994) in the development of a knowledge system that allows a user to select a "subsurface water system"

model suitable for their particular problem. Data are input once and held within the system and are therefore available for use by a different model if required. The knowledge system is driving the model choice and not the user.

Most systems are human health oriented but some do exist that are ecologically based. An example is a system that determines the risk of groundwater contamination by nitrate and the effect that may have on a pine forest (Leimbach, 1994).

There are also some systems that are aimed at the interpretation of legislation and standards. An example of the former is the USEPA's 'Reg-In-A-Box' which was designed to make regulations regarding leaking underground storage tanks more comprehensible to tank owners etc. (Markowitz, 1994). Chung and Stone (1994) have reviewed the use of the knowledge-based approach to accessing, interpreting and applying technical standards.

### **5.3.3 Deficiencies in Knowledge Systems Developed to Date**

Although the previous section details a wide range of systems that have been developed, deficiencies can be identified. The field of environmental knowledge systems is still relatively new (Weckert, 1995) and was considered in 1995 still to be in the "early stages of development" (Mason & Matwin, 1995). In addition, the field of risk assessment has traditionally been focused on human health risks, environmental risk such as risk to groundwater being a relatively recent development. Many systems have not progressed to commercial production or regular use, with some notable exceptions such as RAISON™. There may be many reasons for this, but they may include:

- lack of financial resources to fully develop the system to the commercial stage
- poor problem definition
- developers did not make sure that if development was possible that it was also appropriate and justified
- developers did not use a sufficiently user-centred approach to development
- system developed was usable but did not fulfil user requirements (utility of the system was poor)
- systems were not fully evaluated (verified and validated)

Some systems remain at the proposal stage. For example, a knowledge system was proposed for use in Switzerland to allow remediation resources to be focused on the most high risk sites but was never fully developed (Looser & Parriaux, 1993).

In the literature there is a lack of discussion as to why certain systems fail but the area where most discussion has been generated is lack of problem definition and non-user-centred design. (e.g. Berry, 1994; Shadbolt & Burton, 1995). This research has attempted to recognise these deficiencies of approach.

# CHAPTER 6

## 6 DEVELOPING A SYSTEM AND THE TOOLS REQUIRED

### 6.1 DEVELOPMENT STAGES

#### 6.1.1 Introduction

Developing a knowledge system is not usually carried out by one person. There may be several people involved, such as the end user of the system, the human expert(s) and the knowledge engineer (the person who is developing the knowledge system) (Waterman, 1986: p8). The expert and the knowledge engineer may be the same person (Basri & Stentiford, 1995) The interactions between them are illustrated in Figure 6.1.

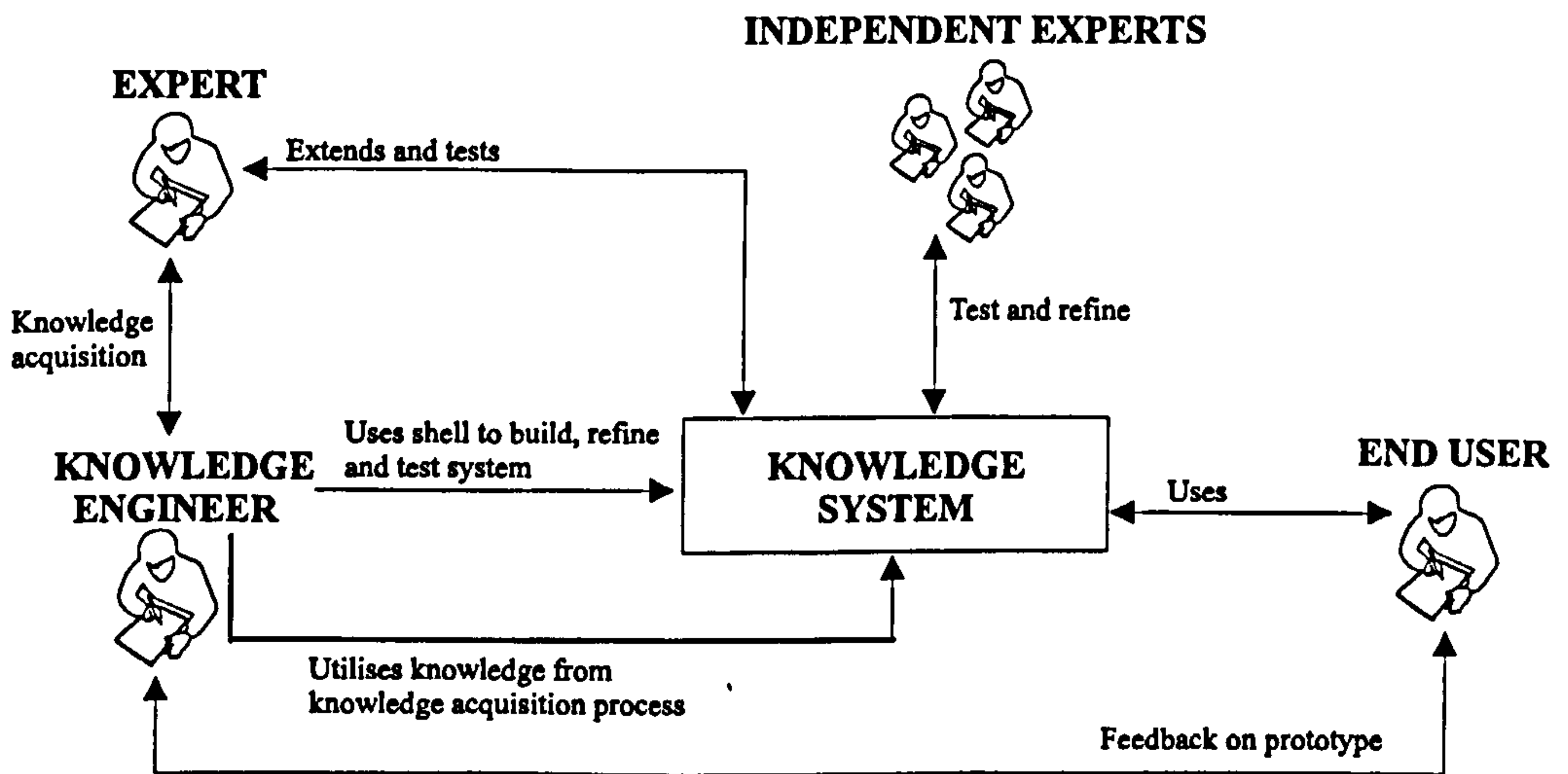


Figure 6.1 : Personnel who may be involved in knowledge system development

In the past there were considered to be five linear stages to the development of a knowledge system (Buchanan *et al.*, 1983), as illustrated in Figure 6.2. Although these stages are listed as happening sequentially, in practice there will be constant redesigns, refinements etc., system development fundamentally being an iterative process.

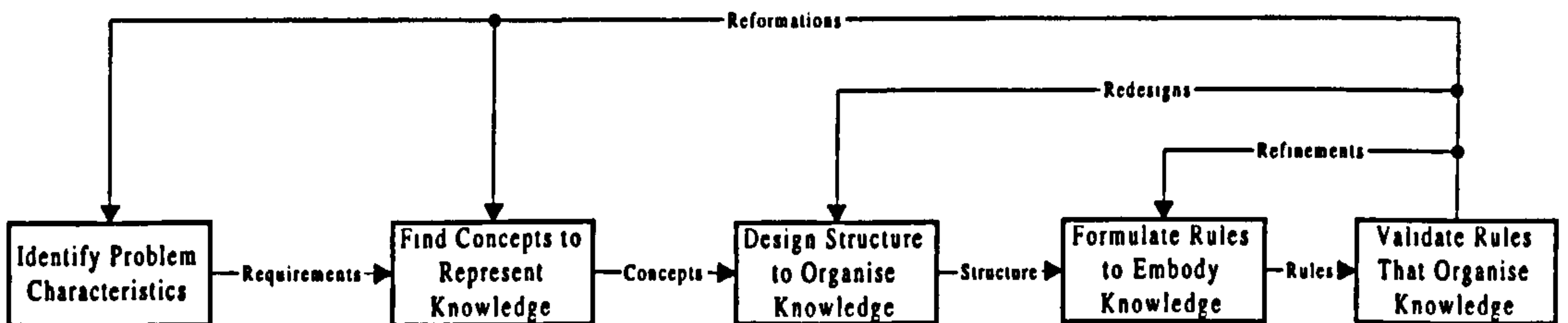


Figure 6.2: Stages of knowledge system development (Buchanan *et al.*, 1983)

*Identification* - the first stage is for the knowledge engineer and the expert to identify the problem in detail: the main objective of the system must be decided, what it is going to do but also what sort of problem it is to deal with. In addition, the resources that will be required must be identified, and if other experts will need to be contacted. Clarifying the scope of the problem is the most difficult part of this stage; if it is too complex, the system will be impossible to construct (Chapter 5, section 5.2.2). Often a small 'sub-problem' is looked at and a system developed around that.

*Conceptualisation* - the knowledge engineer and expert breakdown the problem into concepts and relationships, and decide what problem-solving strategies are to be used and what depth of knowledge is to be represented. This type of conceptual model can be produced before commencing any system programming and can have many advantages: for example, clarification of what exactly the system is about. This stage is often a lengthy one as it incorporates the processes of identifying human expertise and knowledge and developing a conceptual model of the problem area. This stage is critical to successful system development and is discussed further in section 6.2 below.

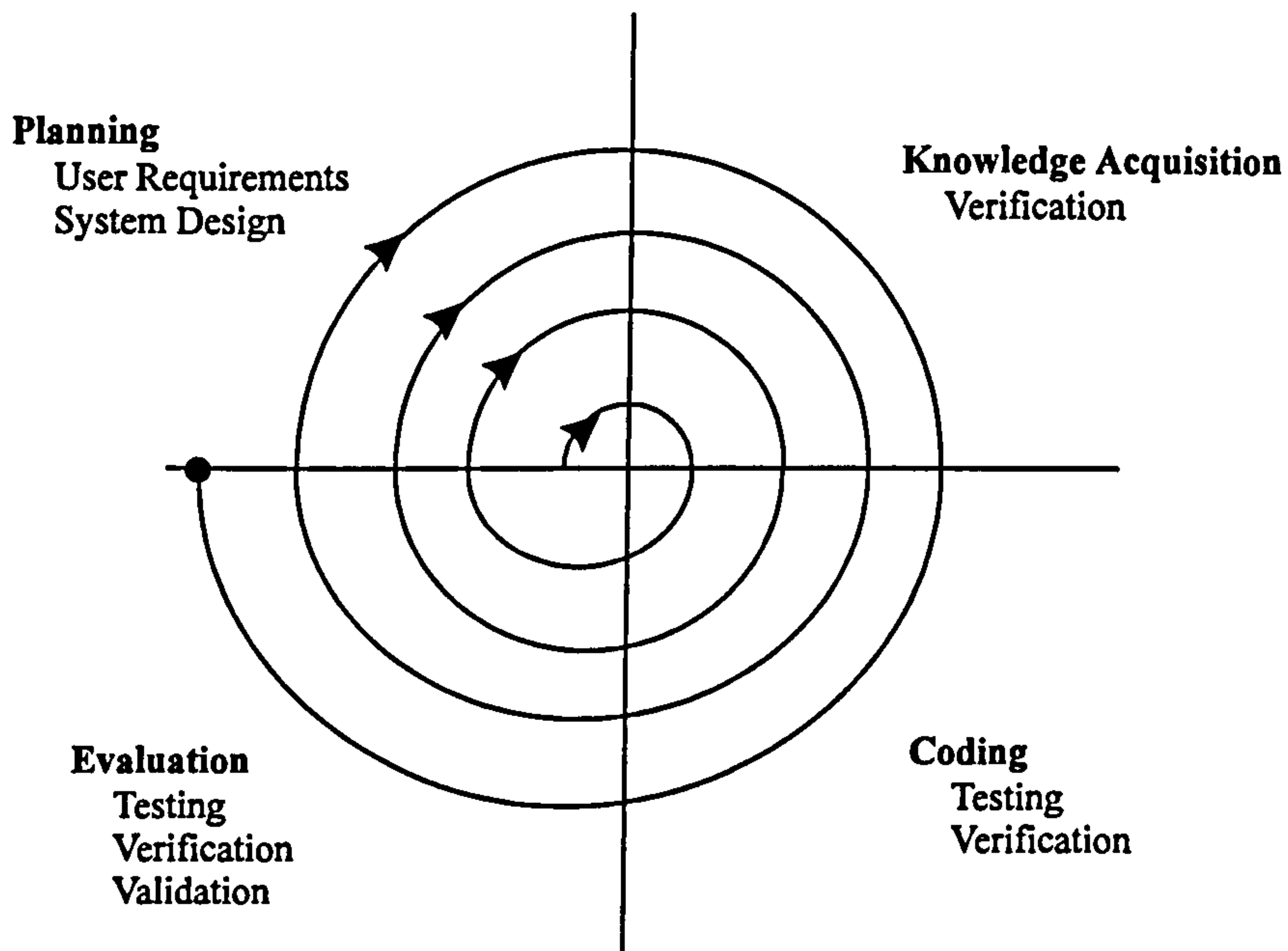
*Formalisation* - this is the representation of knowledge as concepts and relationships in a more formal manner, using an appropriate programming language or a shell (described in section 6.1.5).

*Implementation* - involves the development of a working prototype system with real knowledge in place.

*Testing* - it is highly unlikely that the system developed at the implementation stage will be perfect, so the system must be tested. System performance is evaluated, usually initially by the expert and knowledge engineer together as part of a verification and validation stage.

As the knowledge system field has matured so different modes of development have appeared: for example, the 'Spiral Model' illustrated in Figure 6.3 (Giarratano & Riley, 1989). This model stresses the incremental and iterative development process.

Welbank, (1983: p7) described a *staged* development approach which emphasised the importance of system users and knowledge acquisition activities as part of system development. This method of staged development allows a more natural development process than that formally described by Buchanan *et al.* (1983) and can be overlaid onto the Spiral Model. It is a pragmatic model that has been utilised in actual system development.



**Figure 6.3:** The Spiral Model of knowledge system development (adapted from Giarratano & Riley, 1989: p362)

For a research prototype as developed here, a staged developmental approach is ideally suited, as much attention must be given to the knowledge acquisition phases of system development (with less emphasis on the commercial production stages etc.). The three stages Welbank described are:

*Stage One* - Framing the problem. This includes, finding the experts, getting their co-operation, identifying the users and communicating with both groups. The outcome of this stage is the problem definition. This stage is discussed in more detail in sections 6.1.2 to 6.1.4 below.

*Stage Two* - The knowledge acquisition process. This stage, often termed knowledge acquisition and elicitation, is a complex and lengthy process. As it is so important to successful system development, the various techniques that can be used for knowledge elicitation are discussed in detail in section 6.2 below.

*Stage Three* - Development of the system, knowledge refinement and system evaluation. In order to develop a system, software and hardware choices must be made. A knowledge system can be developed using a programming language, a knowledge engineering language, or a shell environment. Depending on the type of tool, they can be run on a PC or a more sophisticated workstation. The type of tool to be used depends upon several factors such as the experience of the knowledge engineer, and time constraints. The knowledge acquisition process is an iterative one and the knowledge base will undergo constant refinements. The working system must also be evaluated to check if the rules it

contains are correct (verification) and if it achieves the original objectives (validation). This stage is discussed in more detail in section 6.1.5 and 6.1.6 below.

### 6.1.2 Initial Problem Definition

As discussed in Chapter 5 (section 5.2.2), system development must be possible, appropriate and justified: the initial problem definition is critical to answering these type of questions (Waterman, 1986: p127). Other areas important to successful system development include the identification of experts and the involvement of users (e.g., Kidd, 1987; Neale, 1988; Basden, 1994). Table 6.1 illustrates the type of question to be addressed at the initial problem definition stage.

**Table 6.1:** Questions to be addressed during Stage 1 (framing the problem) of system development (adapted from Neale, 1988)

No.	Question
1	Is knowledge system development possible?
2	Is knowledge system development justified?
3	Is knowledge system development appropriate?
4	Who are the potential users of the system?
5	Who are the experts in the problem area?
6	What are the problem boundaries?
7	What is the problem language?
8	Are there any relevant paper-based information sources e.g., textbooks?
9	What hardware and software is available?
10	Has any similar research been reported in the literature?

Questions (shown in Table 6.1) were not considered in any systematic way by many early workers but their consideration is necessary to *successful* system development, as opposed to just *possible, justified and appropriate* development. This is especially true of questions four and five: who are the potential users and who are the experts in the field? These questions are addressed in more detail in sections 6.1.3 and 6.1.4.

The question 'what are the boundaries of the problem?' is related to whether development is appropriate or not. The problem area must be manageable (in terms of knowledge acquisition) but still encompass sufficient expertise so the utility of any developed system is not affected (Neale, 1988).

The language of the problem area is a question about the basic terminology and concepts of the problem area. Experts and potential users do not necessarily use the same language and some terms familiar to the knowledge engineer may have a different meaning in the problem area under investigation (Welbank, 1983). A good example of this may be the term 'risk', a term with a variety of interpretations. Familiarity with the problem area terminology and basic concepts on the part of the knowledge engineer, allows the knowledge acquisition process to

proceed at an enhanced rate. This initial familiarity is often best gained by assessing the available paper-based sources of information such as textbooks. Other possible sources for use in the area of groundwater protection could include Environment Agency guidance documents and legislation.

Questions of availability of hardware and software for system development, although not entirely necessary as part of the initial problem definition, can be briefly considered at an early stage (discussed further in section 6.1.5).

The final question proposed by Neale (1988) was that of 'has any similar work been reported in the literature?'. Apart from the obvious problem of not wanting to repeat work already carried out, applications that have already been developed in similar areas to that under investigation can provide useful insights on how to proceed. Chapter 5, section 5.3 presented an overview of system development in the area of groundwater pollution and protection.

A slightly different approach to initial problem definition was proposed by Grover (referenced in Welbank, 1983: p9). Grover suggested producing a 'domain definition handbook' at the start of system development based on the following:

- A general problem description
- A bibliography of reference documents
- A glossary of terms
- A list of experts in the field
- Descriptions of typical case studies or reasoning scenarios

Much of the above information is available from traditional information sources such as books and journals. However, in order to clarify what the problem area is, a human expert must be consulted (Hoffman *et al.*, 1995; Shadbolt & Burton, 1995).

### **6.1.3 Identification & Co-operation of an Expert**

Identification of a suitable human expert who is willing to take part in the project is fundamental to the success of developing a knowledge system. A system can only be as good as the knowledge it has to reason with. Acquiring knowledge from experts is also a time consuming and difficult process (knowledge acquisition). As development progresses, human experts can test the system and extend it where necessary. More than one expert is also needed to validate any system produced. This part of system development is discussed in more detail below (section 6.1.6).

Systems where the knowledge base is built on non-human resources only, such as text books, guidance manuals etc. are often not as adequate as systems where an expert has been involved



(Shadbolt & Burton, 1995). However, the question of who is a suitable expert in the area that the system is to be developed is not always clear-cut. Someone may be identified as having a good reputation in an area, hold a responsible position, be effective and efficient in their problem-solving and be aware of their limitations, however this does not mean that other similarly qualified individuals will always agree with them. It has been observed that asking a group of experts for a consensus opinion is "almost impossible" (Hart, 1986: p21). There are usually many experts in any given field but not all may be suitable to take part in developing a knowledge system.

Identification of an expert is essentially a sampling issue. Sampling has been described by Smith (1975: p105) as "a procedure by which we infer the characteristics of some group of objects (population) through experience with less than all possible elements of that group of objects (a sample)". It would be impossible to identify and gain the co-operation of 'all' groundwater specialists for example. One type of sampling that can account for the particular problems of expert identification is called "strategic informant sampling" (Smith, 1975: p117). There are two sub-types to this method; snowball sampling and expert choice sampling. Snowball sampling allows the researcher to find a representative sample by asking individuals already identified to suggest others who may be suitable to take part. Expert choice sampling asks the expert to make a judgement about an individual or object as to whether they are 'typical' and could be included in the sample (Kish, 1965: p19). Expert choice sampling can be used to identify 'typical events' or case studies.

Another type of approach sometimes used in ethnographic research is that of a 'key informant' (Le Compte & Preissle, 1993: p166). A key informant is most often used in the context of an interview and is discussed further in section 6.2.2.

In addition to identifying and gaining the co-operation of an expert, another crucial stage of system development is the identification of potential users and their requirements and similar methods can be employed to those used to identify experts.

#### **6.1.4 System Users**

The proposed end users of the system and their requirements must be identified (user requirements analysis) for successful and effective system development. Development of a system without full involvement of users can lead to the system's eventual failure, as it may not be suitable for its intended use even though it may solve problems adequately. Roberts (1990), for example, stated that the success of a system will be greatly reduced if the users have no use for it. User requirements should be determined at the start of the development process. However, in practice there is often insufficient consultation with users. O'Neill and Morris (1989) carried out a survey of commercial expert system development in the UK and found that

only 35% of developers consulted with users throughout the project. User feedback to the knowledge engineer is important and what the users do and the tasks the proposed system is supposed to support must be clarified.

The people that may benefit from any system developed must be identified before development begins. For example, the requirements of an expert groundwater team compared to pollution control inspectors operating in the field could be expected to differ due to the variation in the tasks they carry out. In addition to focusing on Agency personnel, possible end-users may include other types of regulator (e.g., local authorities) or external environmental consultants.

Identifying Environment Agency personnel as potential system users, and in particular pollution control officers, the following must be determined (Kidd, 1987; Clarke *et al.*, 1992):

- (a) the different classes of user and their specific needs;
- (c) what do they do, what tasks they carry out at work;
- (d) what information they currently use to carry out those tasks; and
- (b) analysis of their needs, what are their problems in carrying out identified tasks, what sort of information do they think they require.

There is also a need to establish whether the tasks require expert knowledge and whether the knowledge used is 'task specific' (independent of common-sense and general problem-solving knowledge).

By exploring the type of information people use to carry out their tasks and how that information is used to solve problems, the applicability of a knowledge-based approach can be investigated. For example, as potential system users, do Agency officers (Clarke *et al.*, 1992):

- (i) use external information sources; if so,
- (ii) what kind;
- (iii) how often, and
- (iv) is the information they use easy to obtain and understand and/or use?

It is also essential to understand how computer literate potential users are, their attitude to using computers in the workplace, and what facilities are available on a regular basis. If potential system users are expected to share one personal computer (PC) between 20 individuals, most kinds of computer-based system will not be useful to them.

### **6.1.5 Choice of Development Platform**

There are basically three software options for knowledge system development: knowledge or expert system shells; AI programming languages and a more recent advance 'structured development environments'. Choosing the most suitable development platform for a knowledge

system is an important decision. Several authors have attempted to produce general selection guidelines, for example (Waterman, 1986: p143; Palmer & Mar, 1988; Philip, 1991):

- What is the training level of person to develop the system?
- What are the time constraints on system development?
- What are the graphics requirements?
- What are the user interface requirements?
- Does the system need to interface with other software?
- What is the availability of documentation and other developer support?
- What is the maturity of the software (number of years on the market)?

There is a wide variety of software available from programming languages to shells, the general development options are discussed briefly below.

### *Programming Languages*

Many different programming languages have been employed over the years to develop various types of system. They can be divided into 'problem-oriented languages' like C, FORTRAN and PASCAL, usually thought of as conventional programming languages and the 'symbol-manipulation languages'. These include LISP and PROLOG and might be thought of more as 'artificial intelligence languages' (Waterman, 1986: p80; Basri & Stentiford, 1995).

Whatever language is chosen it will offer the knowledge engineer a high degree of flexibility in designing the system albeit that the system must be developed from scratch including the inference engine and user interface. This obviously takes time especially if the knowledge engineer is not an expert programmer. During the 1970's, most knowledge systems were developed on a workstation (as opposed to a PC) using languages like LISP (Durkin, 1993 and 1996).

### *Structured Development Environments*

The next stage up from using PROLOG etc. is the use of knowledge engineering development environments. They are described as 'complete tools for expert system development', as they allow knowledge to be represented in several ways, usually as rules, and provide a support environment such as debugging facilities (Waterman, 1986: p143). The literature discusses many examples of this type of software and it is an active research area with commercial products being updated regularly.

### *Shells*

Shells are knowledge systems with no knowledge base. There is no need for the inference engine or user interface to be programmed, they come as part of the shell. The knowledge

engineer provides only the knowledge base specific to the problem domain. A disadvantage of using a shell is the loss of flexibility in system development and the possibility that the shell chosen will not be suited to the problem. This can occur once the prototyping stage is quite advanced and the system has become very complex (Ahmad & Griffin, 1991).

However, shells are used extensively for knowledge system development despite these disadvantages (Kaula, 1995), as a shell environment allows a non-programmer to develop a system without the need to spend a great deal of time learning a programming language such as C. Furthermore, shell software is likely to be considerably cheaper than the other options.

By the 1980's the majority of knowledge systems were being developed on PCs using a commercial shell software package (Durkin, 1993 and 1996). Currently there are many shells on the market but as with any software their use should be proven and well supported (Basri & Stentiford, 1995). Palmer and Mar (1988) indicate that in choosing a shell, the deciding factors are often; price, quality of documentation and how easy is it to learn how to use the shell, rather than technical ability to solve domain problems.

A shell was chosen for this work, the reasoning behind and the shell chosen being discussed in chapter 7 section 7.3.1 and chapter 9, section 9.3.1.

Irrespective of the platform chosen there are two different development approaches; (i) rapid prototyping, and (ii) incremental prototyping:

#### *(i) Rapid Prototyping*

This method requires little preparation before data are input as an overall model of the system and what it is intended to achieve are not developed before the knowledge acquisition process begins and system development started. Therefore, it is a method that achieves some results quickly. The knowledge acquisition process, inputting of information to the system, and system modifications are carried out simultaneously. This type of approach is often used in 'engineering' situations, where a system is required to do a specific job and the end users will be some form of engineer (Ladiges & Kayser, 1994; Basri & Stentiford, 1995).

The advantage of this type of approach is that it allows a prototype system to be operational quickly, before the knowledge acquisition process is complete and before a complete model of the system has been developed. Disadvantages include 'dead end' development: i.e., a system could be prototyped in this way when there is no clear idea of what it is being developed to do and the knowledge acquisition process is not sufficiently advanced to indicate that the approach is wrong. The end users of the system will probably not take such an active part in system development and this can lead to a less successful system (Kidd, 1987; Roberts, 1990). A

system developed in this way may also be difficult to document (by user manuals) and to update (Clarke *et al.*, 1992).

### *(ii) Incremental Prototyping*

With this type of prototyping a stepped approach ensures that before any information is put into a computer a full conceptual model is developed of the problem domain and the knowledge acquisition process begun. Only then is a computer-based version of the system developed which is then refined and extended (Clarke *et al.*, 1992). It will lead to a more structured system with less 'wasted time' even though it will take longer for a 'real' system to be up and running and be available for evaluation by users etc.

The staged knowledge acquisition process described by Welbank and adapted for this work utilises the incremental prototyping model and represents the iterative nature of knowledge system development. There is however, no 'correct' prototyping method and the discussion continues in the literature (e.g. Jones, Miles & Read, 1996).

Irrespective of the prototyping method is employed, the system produced will require evaluation i.e. it will need to undergo a verification and a validation process.

### **6.1.6 System Evaluation**

System evaluation is shown as part of Stage 3 of system development but in reality the knowledge collected during the knowledge acquisition phase is evaluated as part of an iterative process (e.g., Figure 6.3). Evaluation forms a component of all stages of development. However, the final stage of development does give an opportunity to evaluate the system in a more systematic way. There are two elements to this evaluation: verification and validation of the system.

Verification is the process by which the system is checked for its correctness, completeness and consistency (Giarratano & Riley, 1989: p368). Waterman (1986: p138) proposed the following questions to verify a system:

- are the rules correct, consistent and complete according to the expert?
- does the system make decisions that the expert would agree with and that are appropriate to the situation?
- does the system 'do' things in a sensible order, does it ask 'inappropriate' questions?
- is the explanation facility good enough to explain how and why a decision was made by the system?
- are there problems suitable to test the system?

By going through this checklist with the expert, gaps in the knowledge, incorrect rules, poor explanations etc. can be identified and corrected. To avoid introduction of any undue bias the system should also be verified by an independent expert, someone who has not taken part in the knowledge acquisition phase. This process can highlight areas of professional disagreement but also compares the different problem-solving strategies that experts have. Once a system has been verified then validation can take place.

Validation is the process by which the system is checked for its 'usefulness' or utility and whether it fulfils the original design objectives. This can be done by surveying potential users (e.g. Clarke *et al.*, 1995). The utility of the system can be tested by the following type of questions (Waterman, 1986: p136; Giarratano & Riley, 1989: p369):

- does solving the problem actually help the user?
- are the systems answers presented in an understandable way and at the right level of detail?
- is the system fast enough for the user? and
- is the user interface easy to use?

These verification and validation questions can be asked throughout the development phases and lead to refinement of the system by iteration. By developing a conceptual model of the problem area and conducting a user requirements study it is hoped that many of these questions can be answered satisfactorily before the final evaluation stage. For example, Roberts (1990) stated "the chances of producing a successful system are greatly reduced if potential users do not want it", finding out what they do want and implementing it, is part of the on-going system development process, verification and validation being part of that process (Preece, 1990).

However, system evaluation is still not a standard part of system development (Geldof, Slodzian & Velde, 1996) even though its use as a measure of system quality has been recognised by many workers (e.g. Lydiard, 1992; Mengshoel & Delab, 1993). Berry and Hart (1990b) state that the evaluation process should not be left until the system is in use but should be an integral part of the development process. The main focus of the development process, however, remains knowledge acquisition and elicitation.

## **6.2 KNOWLEDGE ACQUISITION AND ELICITATION**

### **6.2.1 Introduction**

The knowledge that is to be part of the system must be captured in some way, a process called 'knowledge acquisition'. Knowledge acquisition has long been termed the 'bottleneck' in knowledge system development (Feigenbaum, 1983). It is a difficult and time consuming

process due to the nature of trying to model human expertise and the difficulty of using the techniques available to do this.

Knowledge acquisition and the transfer of knowledge is a highly complex and poorly understood process and not just in relation to development of knowledge systems. There is a large body of literature detailing research methods that can be used, for example, interviews, questionnaires, ethnographic-based research methods such as participant observation etc. There are many texts on research methods, when and how to use them (e.g., Gill & Johnson, 1991; Oppenheim, 1992; Banister *et al.*, 1994). Most of the techniques that have been used in knowledge system development are of course not unique to this field. Techniques such as interviewing or rating of concepts have been adopted from the fields of social science and psychology research and modified to suit this context.

The actual process of trying to model expert knowledge utilises a variety of information sources such as journal papers, text books and people and is called knowledge acquisition. Gathering information from human experts has been described as a 'sub-task' of knowledge acquisition and termed knowledge elicitation (Shadbolt & Burton, 1995). It is this sub-task of knowledge acquisition that is very important to the successful development of a final system but the methodologies used by many workers are often poorly discussed (Neale, 1988) or there is over-reliance on one technique. Some possible reasons for this have been put forward (La France, 1986):

- (a) lack of understanding about the nature of expertise
- (b) poor manual interviewing skills, lack of interpersonal and communication skills
- (c) limited repertoire of questioning strategies, lack of probing questions

In a survey carried out by Moula, Toll and Vaptismas (1995) of knowledge system development in the field of geotechnical engineering, twenty-nine systems were reviewed. In fifteen, the knowledge acquisition method utilised was described by the original authors. Only three techniques were used: literature review, interviews and questionnaires. Of those fifteen systems, only six used two techniques and none used three.

In the past, the process of elicitation has been described as "extracting knowledge from an expert and transferring it to a program" (Buchanan *et al.*, 1983). The attitude that knowledge acquisition is just a process of 'knowledge extraction or knowledge mining' has led to developmental problems and poorly designed systems (Kidd, 1987). The aim of the knowledge acquisition process as a whole should be to model expert knowledge (i.e. how they think) not just extract data and encode it into a program (Berry & Hart, 1990a). It has been argued that it is not even modelling of expert knowledge that is the aim of knowledge acquisition but the modelling of expert performance and competence that is critical (Johnson & Johnson, 1987).

There is a vast array of different elicitation techniques that can be used as part of the knowledge acquisition process when developing a knowledge system. No one technique will work in all problem areas and with all experts: there is no "magical technique" (Kidd, 1987). The practice encouraged by a variety of authors is to take a 'toolkit' approach to knowledge acquisition and to choose techniques that are suited to the problem domain and chosen expert(s) (Mitchell, 1986; Kidd, 1987; Shadbolt & Burton, 1995). The use of multiple knowledge acquisition techniques has been advocated in order to obtain the 'richest collection' of information about expert knowledge used in the problem area (Kidd, 1985). However, there is little or no guidance as to which techniques should be used for which types of problem area. It is only relatively recently that research has been conducted to compare the success of different elicitation methods (Holsapple & Raj, 1994; Hoffman *et al.*, 1995; Jones, Miles & Read, 1996). This lack of guidance may be due in part to the relatively young age of the field of knowledge system development and the fact that many suitable knowledge acquisition techniques were originally developed in the social sciences and the field of psychology: not areas of expertise for many computer scientists.

Unlike the field of social science research, knowledge system development has yet to develop clear theories of knowledge acquisition: i.e. which technique to use for which type of problem (Gaines, 1986; Cooke, 1994). Some workers have attempted to provide frameworks for system development that are not problem specific but can be applied to a wide range of domains. One such example is the KADS methodology (Knowledge Acquisition and Documentation Structuring) (Breuker & Wielinga, 1987). The KADS methodology tries to provide a structured and systematic approach to knowledge acquisition and system development by separating out the problem analysis phase from the design, implementation and testing stages. Breuker and co-workers (1987) have identified certain elicitation techniques that can be used for certain phases of the KADS methodology (e.g. the structured interview for problem identification) and no one technique is relied upon for all stages of development.

Shadbolt and Burton (1995) have identified a range of techniques (from the fields of social science and psychology research) that have been useful to them for knowledge system development and have divided them into 'natural' and 'contrived' techniques. A natural technique would be one that an expert might use when applying their own expertise, such as interviewing. A contrived technique such as concept sorting, requires the expert to express expertise in ways that they would not normally. Table 6.2 lists some examples of natural and contrived elicitation techniques. A variety of techniques were utilised during this work. The techniques used and the reasons why are described in Chapter 7, section 7.2. Their general basis and use is introduced here.



**Table 6.2:** Examples of contrived and natural knowledge elicitation techniques that can be used as part of the knowledge acquisition process (Belkin, Brooks & Daniels, 1986; Neale, 1988; Neale & Morris, 1988; Shadbolt & Burton, 1995)

Natural Techniques	Contrived Techniques
<i>Interviews</i>	<i>Conceptual Mapping</i>
Structured	Concept sorting
Semi-structured	Rating and ranking
Unstructured	Repertory grid analysis
<i>Protocol Analysis</i>	Delphi technique
Verbal - 'on the job'	<i>Goal decomposition</i>
Verbal - 'off the job'	Laddered grid
Shadowing	Limited information task

## 6.2.2 Natural Techniques

### *Interview Techniques*

Interviewing is probably the most frequently used technique in the knowledge acquisition process (Neale & Morris, 1988) and is often used as a starting point (Shadbolt & Burton, 1995). Interviewing is obviously a well-established research method with general guiding principles of operation (e.g. Wragg, 1978; Oppenheim, 1992). The interview has several forms in qualitative research but its use for knowledge system development is probably closest to the 'ethnographic interview'.

Ethnography has its roots in anthropology and is an approach to carrying out qualitative research, often in the field of social psychology, "which combines several methods, including interviewing and observation" (Fielding, 1993). The Collins English Dictionary defines ethnography as "the branch of anthropology that deals with the scientific description of individual human societies". The researcher is interested in the "meanings people apply to their own experiences" where ethnography involves the study of people's behaviour in a 'natural setting' (Fielding, 1993) i.e. the study of groups and the social relationships between group and behaviour. Therefore in the current context, using an ethnographic interview approach will highlight a person's expertise and give access to that person's subjective rules of behaviour within a certain social group (Banister *et al.*, 1994: p34 & p52).

One type of ethnographic interviewing is the 'key informant' interview. Key informants are "individuals who possess special knowledge, status or communicative skills and who are willing to share that knowledge and skill with the researcher" (Le Compte & Preissle, 1993: p166). Spradley (1979: p45) also advocates the use of an informant. A 'key informant' in the context of knowledge system development and this research, most closely describes the 'principal expert'; the person providing the model of expertise on which the system is based.

There are differences between an ethnographic approach to interviewing (and the ethnographic approach as a whole) and that used in knowledge system development. An ethnographer

participates in the research but does not structure it and only aims to discover and be able to depict activities (Banister *et al.*, 1994: p34; May, 1993: p116). In contrast, a knowledge engineer is actively trying to impose a structure on the research, whilst discovering activities, as a knowledge system is a structured model of expertise.

There is a large body of literature detailing interviewing as a research method, however, while there are fewer guidelines for the specific use of interviews for knowledge system development, the literature does contain some practical guidance (e.g. Davies & Hakiel, 1988). Interviewing as a research method, is useful for acquiring background information and for finding out the reasons why something is done the way it is. Interviews are sometimes thought of as "structured conversations with a purpose" (Dane, 1990: p128). They are generally faster than observational methods (e.g. shadowing) and in terms of knowledge acquisition, the expert can be questioned about 'rare events' that may be missed by using observational methods (Welbank, 1983: p19).

The interview itself has been categorised in a variety of ways; on the basis of who is being interviewed or by the purpose and structure of the interview (Le Compte & Preissle, 1993: p169). For the purpose of knowledge system development, the most common interview categorisation used is broadly based on that of Denzin (1970: p123; e.g. Neale, 1988; Cooke, 1994; Shadbolt & Burton, 1995):

- Structured interview (or scheduled standardised interview)
- Semi-structured interview (or non-scheduled standardised interview)
- Unstructured interview (or non-standardised interview)

The structured interview is based on a 'schedule' where all the questions to be asked are written out in detail before the interview takes place. The schedule might consist of cards given to the participant requiring short responses (Dane, 1990: p128). The technique is useful when a quick response is required or when following up a written questionnaire. The method can be restrictive and hence frustrating to both interviewer and respondent. In a knowledge acquisition context (as opposed to the use of interviewing for market research for example) the knowledge obtained by a structured interview may not be truly representative due to questions and answers being 'forced' into a certain pattern and for this reason it is not felt to be a particularly useful method of knowledge acquisition for knowledge system development (Neale, 1988).

The semi-structured interview format also relies on a pre-prepared schedule but the method allows for greater flexibility on the part of the interviewer and the interviewee (Dane, 1990: p129). The respondent (in a knowledge acquisition context, often the expert) can express themselves in their own words and at their own pace. The method also allows the interviewer to follow-up any interesting points (Wragg, 1978) and the respondent to "develop their views at

length" (Moser & Kalton, 1971: p298). Unlike the structured format, the direction of the interview may be more difficult to control making subsequent analysis harder but this is balanced by the greater flexibility of the method. The semi-structured format is the one most utilised in knowledge system development.

There are a wide variety of techniques and questioning strategies loosely based on the semi-structured format that have been used in this context:

- **Knowledge Acquisition Grid** - developed initially as a training exercise for novice knowledge engineers (La France, 1986). The grid was developed to deal with the difficulty of categorising expertise into types and the fact that no one question can elicit all the information. One dimension of the grid represents the 'forms of knowledge' or how the expert stores their knowledge, and the other dimension includes the question types that the knowledge engineer can use to elicit that knowledge. The knowledge acquisition grid leads to a more systematic process and greater efficiency.
- **Critical Incident** - the expert is asked to describe a particularly memorable event (case study) in detail. They could be asked to describe what guidance they would give to an inexperienced person trying to solve the same complex problem that they thought of. Experts will find it relatively easy to think of cases and will be able to talk about them (natural as opposed to contrived, Welbank, 1983: p19). However, the interviewer may find it difficult to control the discussion and when it comes to the analysis phase, it may be difficult to generalise from an expert-specific case (Neale & Morris, 1988).
- **Teachback Interview** - the expert describes a procedure and the interviewer 'teaches it back' to him using the expert's terms and to his satisfaction. This technique was originally adapted from conversation theory to knowledge system development by Johnson and Johnson (1987). The technique is useful for obtaining the concepts of the domain as the expert sees it, without bias from the interviewer. It is non-judgmental of the expert and encourages good interview practice. As a technique it does require some training before use and it can be very tiring for the interviewer. In addition, large amounts of transcript data are produced making analysis a lengthy process (Neale, 1988).

The unstructured interview has no planned schedule and may just be focused on an 'area' to be discussed. The interviewer provides little or no guidance and few direct questions (Dane, 1990: p130). The format may allow information to be elicited that would otherwise have been missed. It is a technique that requires greater skill on the part of the interviewer (Wragg, 1978) and has the obvious disadvantage that it is much harder to focus questions and answers, hence making analysis more difficult. In the knowledge acquisition context this format is sometimes

useful when trying to build a relationship with an expert so as to gain support and co-operation (Shadbolt & Burton, 1995).

La France (1986) discussed why using interviews as an elicitation method for knowledge system development may not always be successful (whatever format is used). Just asking an expert 'why' repeatedly will not generate useful information and may alienate the expert. This response is not exclusive to the field of knowledge systems and 'probe questions' can be utilised to avoid this problem. Probes have been described as "phrases or questions used by the interviewer to prompt the respondent to elaborate on a particular response" (Dane, 1990: p130). Shadbolt and Burton (1995) suggest a selection of probing type questions that can be utilised for knowledge system development:

- Why would you do that?
- How would you do that?
- When would you do that?
- What alternative actions are there?
- What happens if 'x' is not the case?
- Tell me more about 'x'?

Using questions like this during an elicitation interview means that the process is likely to be more efficient in obtaining the necessary information from the expert.

A variation upon a interview is the Delphi Technique. The Delphi Technique in effect allows someone to 'interview' themselves. The technique relies on a group of participants taking part in the whole process. Participants are asked to respond to a specific issue independently of each other. This can also be done via a questionnaire being sent to each respondent with many 'open-ended' questions (Mostyn, 1985). Responses are analysed and summarised. The questionnaire is then sent out again but this time with a summary of the previous responses and participants are asked to reconsider the issues bearing in mind those responses. This process is then repeated. The technique can be used to seek solutions by eliciting a consensus view or by ranking or categorising responses (Robson, 1993: p28). The technique, however, does produce large amounts of textual data for analysis.

### *Protocol Analysis*

Protocol analysis is a form of systematic observation and as a research method allows behaviour to be observed without researcher participation (Dane, 1990: p146). It is a well-known technique used in psychological research, sometimes referred to as 'verbal reporting' (Ericsson & Simon, 1984: p1). These type of methods are particularly suited to exploring and describing a research area. In the context of knowledge system development, protocol analysis generally involves the expert being asked to 'think aloud' as they solve a problem. What the

expert says is recorded and transcribed into a 'protocol' and analysed for structure and rules (Neale, 1988; Shadbolt & Burton, 1995). It is a natural technique for the expert and it can be performed in several ways:

- *'On the job'* - traditional protocol analysis where a real problem is solved in real time and the expert does not try and explain why they are doing something (also called *concurrent verbal reports* (Ericsson & Simon, 1984: p16)
- *'Off the job'* - typical case studies are worked through 'out loud' (also called *retrospective reports* (Ericsson & Simon, 1984: p16). The case studies can be chosen by the expert or by the knowledge engineer. Welbank for example recommends the case studies are provided for the expert so they are unfamiliar with them (Welbank, 1983: p21)

Protocol analysis can be used to follow up interviews and to see if the expert does what they said they do. It is a useful technique for obtaining procedural knowledge: the 'when' and 'how' of solving the problem (Shadbolt & Burton, 1995).

Important to both methods is the choice of problem to be described by the expert. They should be as representative or typical as possible, as the technique is tiring for the expert and time consuming (exact timing depends on the problem but even a relatively simple problem can take over an hour). Protocols often do not cover the 'rare events'. Even relying on the technique to describe typical events may not be without problems as the information that is collected may be incomplete, the expert may not state what he sees as 'the obvious' or he may simply miss out steps in his reasoning process (Welbank, 1983: p23).

### 6.2.3 Contrived Techniques

#### *Repertory Grid Analysis*

Repertory grid analysis was originally developed as a model of human thinking called 'Personal Construct Theory' by Kelly in 1955 . He proposed that everyone has their own personal model of the world and the repertory grid technique is a method of eliciting that model (Banister *et al.*, 1994: p73). This technique has been used in knowledge system development even though as it represents a personal view, the results could be considered subjective. If two experts try and solve the same problem, different results are highly likely if repertory grid analysis is used, this difference in outcome can be used to investigate the problem area further (Hart, 1986: p133).

A set of objects (elements) relevant to the problem area are collected (not necessarily from the expert) and presented to the expert who is asked to say why one is different from the others. Elements are usually (but not always (Fransella & Bannister, 1977)) presented in threes, these being chosen systematically or randomly (Banister *et al.*, 1994: p76). The difference that the

expert says lies between three elements is a construct and is bipolar, i.e., heavy/light along an ordinal scale (e.g. 1 to 3 or 1 to 5, shown in Figure 6.4). Every other element is then rated according to that construct. These numbers have no absolute meaning and are merely used by the participant to describe the relative positions of the elements (Banister *et al.*, 1994): p77). A grid can be completed without using a rating scale but some of the subtlety of the method is lost (Neal & Tyrell, 1979). The process of eliciting constructs for triads of elements continues until all elements have been rated and a grid completed (Neale, 1988). The grid can then be analysed to investigate relationships between the elements and constructs.

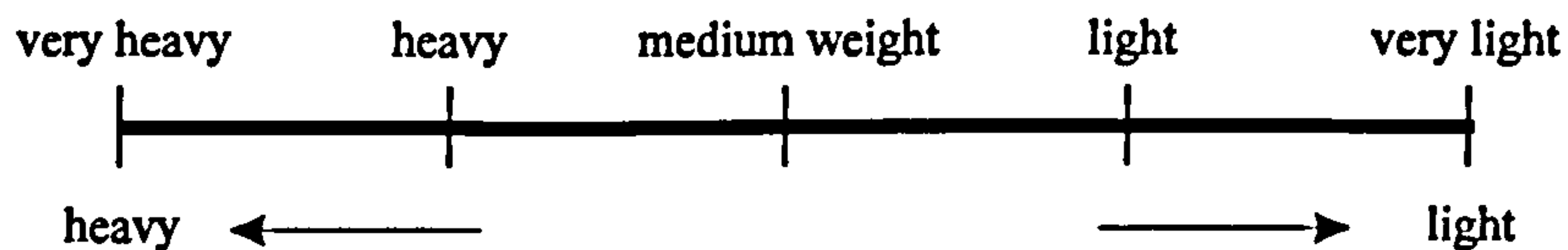


Figure 6.4: A bipolar construct and example ratings (Hart, 1986: p135)

There are several methods of grid analysis, such as factor analysis and principal component analysis, which can be done manually or by computer (Leach, 1988). A relatively simple method is cluster analysis that can be used when an ordinal rating scale has been used to complete the grid (Banister *et al.*, 1994: p77). This method has been utilised successfully in knowledge system development (Shaw & Gaines, 1987a). Analysis is usually done automatically using a variety of computer programs that can analyse a single grid, paired grids or a group of grids. The technique has also been used as part of automated knowledge acquisition programs such as KITTEN which takes the user through the complete knowledge acquisition process (Shaw & Gaines, 1986; Shaw & Gaines, 1987b).

There are some difficulties with the technique. The lack of subjectivity has been acknowledged above. Using more than about ten elements makes both completing the grid and the subsequent analysis difficult (Banister *et al.*, 1994: p76). If automated techniques are used there may be a tendency to lose sight of common sense in the face of mathematical capability (Neale, 1988). However, the technique is useful for gaining an individual's insight into the problem at the overview level, is relatively easy to administer and most useful during the early stages of knowledge elicitation to enable the expert to express concepts and principles (Hart, 1986: p137 & p152). It has been used in industry to some effect (Stephens & Gammack, 1994) and this may be due to the fact that it may be more efficient than structured interviewing for gaining that overview or 'getting started' on the knowledge acquisition process.

### *Concept Sorting*

This technique, like repertory grid analysis, is a method for investigating the relationships between objects or concepts in the problem area and has been used in the area of psychological research for many years (Canter, Brown & Groat, 1985). In terms of knowledge system development it is a way of investigating how the domain or problem area is organised (Benfer,

Brent & Furbee, 1991). As discussed earlier, the interview, as an elicitation technique will not be able to capture the non-verbal information, and the use of concept sorting can be utilised to investigate this. It has been used to study the differences between an expert and 'novices' (Glaser & Chi, 1988; Hoffman *et al.*, 1995) and can be used with several experts and their results aggregated (Cooke, 1994).

The first stage in using this method is the concept elicitation phase. Concepts to be sorted must first be identified and printed onto cards for sorting. This initial elicitation phase can be carried out in several ways: e.g. as a tutorial interview (Gammack, 1987) by concept listing, by step listing and by chapter listing (Cooke & McDonald, 1986).

Using a *tutorial interview* as an elicitation method, the expert is asked to describe to the knowledge engineer an outline of the problem area or talk through some case histories. The session is recorded and a list of concepts is taken from the transcript. Methods such as concept listing, require the expert to record on paper all the concepts he thinks are important to the problem area (not necessarily in order). *Step listing* requires the expert to describe the actual steps he takes when problem solving and *chapter listing* requires the expert to provide a list of chapter and subheadings that they would use if they were writing a book about the problem. Comparison of these methods showed that interviewing was most effective at eliciting concepts (Cooke & McDonald, 1986).

Once printed onto cards, concepts can then be sorted into 'piles' of a fixed number or as many as the expert thinks are necessary with the expert labelling each pile (Shadbolt & Burton, 1995). Card sort methods can be adapted to many different domains. Some workers have stated that experts find it relatively natural and easy (Gammack, 1987), others dispute this, however, if an expert can not seem to get the sorting to 'work' they may become irritated. Neale (1988) and Shadbolt & Burton (1995) state that experts tend to be suspicious of such a technique. Another weakness of this technique is that as it is hierarchical it may be restrictive to the expert, for example, a concept may fit into more than one category but it can only be sorted into one pile (Gammack, 1987). Interestingly Shadbolt & Burton (1995) also found that even if an expert feels that they are not performing well using the card sort technique, on analysis this is usually found not to be the case.

### *Ranking and Rating Scales*

The ranking and rating of concepts, commonly called scaling techniques are popular and well-established methods in the fields of social and psychology research. Scaling methods can be used to provide a level of 'measurement' of a concept: e.g., Thurstone scales, Likert scales and Q-sort scales (Robson, 1993: p255). The Q-sort scale can be particularly useful for knowledge system development. This technique can be used "to measure an individual's relative

positioning or ranking on a variety of different concepts" (Dane, 1990: p280). The Q-sort scale is very similar in process to the concept sort technique described above, except concepts are rated on a scale of 1 to 5 for example and not physically placed in 'piles'. The Q-sort scale technique allows for a larger selection of concepts to be included. Some authors do not differentiate between a concept sort and a Q-sort using a scale (e.g., Cooke, 1994) and in practice a concept sort can be used to feed into a more sophisticated Q-sort based rating exercise.

The starting point for this technique is elicitation of a set of concepts to be rated or ranked. The method has been used in a variety of areas e.g., highway engineering and livestock judging and in comparing experts and novices from the same domain (Hoffman *et al.*, 1995). By using a simple rating or ranking exercise the expert is able to give an estimate of 'relatedness' between different concepts which may highlight differences from the estimates of 'relatedness' obtained by other methods e.g., repertory grid analysis. A matrix can be produced where the rows represent different concepts and by summing across the rows, data from more than one expert can be combined (Cooke, 1994). This kind of information can sometimes be used to generate confidence factors (Benfer, Brent & Furbee, 1991).

The main disadvantages of concept sorting such as restrictiveness due to its hierarchical nature apply to the ranking and rating of concepts too. Using a technique such as the Q-sort becomes difficult with a large sample and such sorts are often only carried out with a small group of respondents. The Q-sort in particular is a very useful exploratory technique even with these limitations (Dane, 1990: p282).

#### **6.2.4 Observations on Techniques**

Knowledge engineers have traditionally relied on interview techniques and perhaps some observational work, for example protocol analysis, to acquire their particular domain knowledge (Welbank, 1983). This approach has been criticised as being inefficient (Cooke & McDonald, 1986; Hoffman *et al.*, 1995). Techniques such as interviewing can only elicit verbal knowledge, therefore, if an expert cannot describe something in words (tying a shoelace has been used as an example) it will not be elicited during an interview. Related to this, is the fact that human experts often use automatic or compiled knowledge (Shadbolt & Burton, 1995). This knowledge may have been learnt in an explicit fashion - for example, I do this..., then I do that... - but over time and as experience develops, this knowledge becomes compiled, and implicit and the expert may no longer be able to actually say how he carries out some task - i.e. the intermediate steps from a to b are done automatically. Expertise may appear to be intuition (Cooke & McDonald, 1986) and may be expressed as 'gut-feeling'. This type of knowledge is extremely difficult to represent as 'if-then' rules as part of a knowledge system. In addition to the difficulties of experts not being able to express their knowledge, they may not always



actually do what they say they do (Gaines, 1986). They may contradict themselves, use inconsistent explanations (Hart, 1987) and not explain the domain-specific terminology (e.g., the term 'risk'). The use of techniques such as repertory grid analysis and concept sorting, in addition to interviewing for example, can be used to elicit knowledge from an expert, enabling a more complete and accurate picture of the problem area to be developed (Cooke, 1994).

The literature contains many examples where knowledge elicitation has not been a totally successful exercise. A particularly pertinent example is that of Keeney and von Winterfeldt (1989) involved in a study of nuclear safety and elicitation of probabilities. Weaknesses identified in the original elicitation process included:

- failure to identify target issues for discussion
- failure to use state-of-the-art assessment methods (used unstructured interviews for example)
- failure to document the elicitation process adequately
- underestimated time required for analysis of elicitation process

The main reasons Keeney and von Winterfeldt (1989) identified for these weaknesses were that the whole process of eliciting expert judgement was done in an informal way. When the process was carried out again, a formal procedure was developed as follows:

- the issues to be discussed were identified carefully before discussion sessions took place using explicit criteria
- experts selected were representative of the problem area and included technical specialists and generalists; issues were refined with the experts
- elicitation was undertaken by analysts with training in cognitive psychology who used semi-structured interview techniques
- the elicitation sessions were taped
- sufficient time was allocated for analysis of the elicitation process

The characteristics of 'expertise', 'experts' and 'knowledge' have obvious implications for the development of a knowledge system which aims to model the human reasoning process. Broadbent (1989) discusses the need to represent declarative and procedural knowledge when developing a knowledge system. It is the procedural knowledge that is often more difficult to elicit but it is this type of knowledge more than declarative knowledge, that denotes an expert. Both types of knowledge must be elicited and represented within a knowledge system in order for it to function as a decision-support system.

As the knowledge acquisition process is so important to knowledge system development, but is so time consuming and difficult, much research effort has gone into developing automated

knowledge acquisition aids. The emphasis has shifted away from 'direct contact' with the expert(s) to the use of computer-based development tools (Jones, Miles & Read, 1996). The latter can be utilised in a wide range of problem domains, to supposedly remove the element of an inexperienced knowledge engineer selecting inappropriate elicitation methods and make the process of knowledge acquisition more efficient. Some examples include KITTEN (Knowledge Initiation & Transfer Tools for Experts and Novices, Shaw & Gaines, 1987b) KA<sup>2</sup> (Knowledge Acquisition Advisor, Feng & Weber, 1993) and KADS (Knowledge Acquisition and Design Structured methodology, Hayball & Barlow, 1990).

KADS was developed to support the development of commercial knowledge systems. Strictly speaking it is a complete prototyping tool that designs the system as well as the knowledge acquisition phase. The KADS methodology was briefly discussed in section 6.2.1. As it is a structured methodology, system development should be more ordered and efficient and the use of the KADS methodology also ensures the user is not ignored. Although such a structured methodology can only enhance the development process, others have noted that considerable training and experience is required to become proficient in using such a methodology - the KADS approach does not provide a "magic wand" solution (Kingston, 1995). This observation was also made previously about more traditional elicitation techniques (Kidd, 1987).

Although it is recognised that automated elicitation techniques may offer a more structured approach in certain circumstances, it was felt that more traditional techniques should be used for this research, for a number of reasons, including:

- Methodologies such as KADS were developed for commercial knowledge systems (Kingston, 1995) - HARRIS was developed as a research prototype
- As HARRIS is a research prototype the cost of additional software/hardware that would be required, could not be justified (Ahmad & Griffin, 1991)

The use of multiple techniques in the knowledge acquisition process ensures that the model of the expert's knowledge is as accurate as possible and the use of an incremental prototyping as part of the development method also supports this (Cooke, 1994).

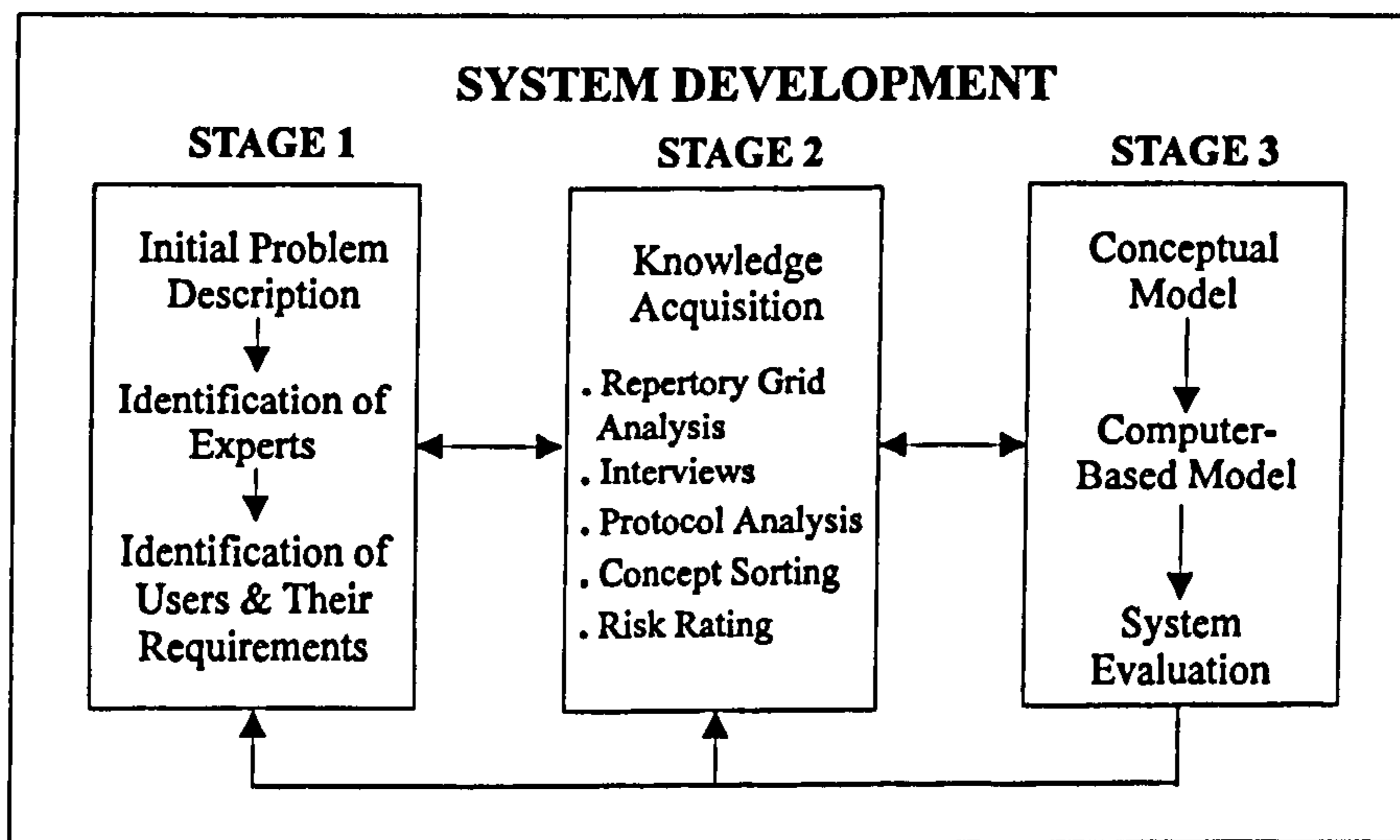
## CHAPTER 7

### 7 SYSTEM DEVELOPMENT - DERIVING THE KNOWLEDGE

The development approach adopted during this research has emphasised knowledge acquisition activities and potential system users. This approach has been cited widely as being useful to successful system development (e.g. Kidd, 1985; Hart, 1986; Shadbolt & Burton, 1995). There are three main stages to development:

- Stage 1 - Framing the problem
- Stage 2 - Knowledge acquisition and conceptual model development (conceptualisation)
- Stage 3 - Prototype development (implementation and evaluation)

The first stage is a detailed definition and characterisation of the problem area, to assess whether it is suitable for a knowledge-based approach. This is followed by identification of experts and potential system users. Once these tasks have been achieved the knowledge acquisition process can begin, leading to the formation of a paper-based or conceptual model of the problem domain. The final stage encompasses the actual prototype development. Although represented as a linear development process, in practice some phases become cyclical e.g., information elicited during stage two could affect the original problem definition. The process that occurred during this research is represented by Figure 7.1.



**Figure 7.1:** A representation of the overall systems development process utilised during this research

The methodologies used for the three main stages are discussed in more detail in the following sections.

## **7.1 STAGE 1 - FRAMING THE PROBLEM**

### **7.1.1 Problem Characteristics and Definition**

As discussed in Chapter 5, section 5.2.2, knowledge system development must only be considered if that development is possible, justifiable and appropriate (Waterman, 1986: p127). Historically, these questions have been addressed in that order, assessing the possibility of development first. In practice, the key point is that all questions must be addressed before development starts and the question order is not so important. In addition to these preliminary questions, there are several other areas that must be considered in the first phase of development, such as the identification of experts and potential users. Table 6.1 (Chapter 6, section 6.1.2) lists the type of questions that have been considered by previous workers, clear answers to which have been seen as necessary to a successful system (e.g. Kidd, 1987; Neale, 1988; Hushon, 1989; Laufmann, De Vaney & Whiting, 1990; Clarke *et al.*, 1992). The questions listed in Table 6.1 were considered as part of stage one of system development for this research. In addition to the questions posed in Table 6.1, the initial stages proposed by Grover (1983) as referenced by (Welbank, 1983) were also utilised (Chapter 6, section 6.1.2).

- A general problem description
- A bibliography of reference documents
- A glossary of terms
- A list of experts in the field
- Descriptions of typical case studies or reasoning scenarios

In this research, information required to complete this first stage of development was obtained from a variety of sources but focused on a detailed literature review and face-to-face interviews with those experienced in the 'problem' area, of decision-making in the field of groundwater protection and those with experience of knowledge system development. Two particular areas were considered most important to this research; identifying, and gaining the co-operation, of an expert, and identification of users and their requirements. The methodology used for these areas is described in further detail in the following sections

### **7.1.2 Identification and Co-operation of an Expert**

As discussed in Chapter 6, section 6.1.3, the identification of an expert that can take part in the system development process is an important stage of that development process. A set of selection criteria were used to identify what constitutes 'expert status' in the context of this research. Having identified a suitable expert, their co-operation and support for the work must be secured and their interest maintained.

#### *Identification Criteria*

The principal expert was defined as being a regulatory groundwater specialist. A regulatory expert was chosen to be the principal expert as the main objective of the proposed system was to support regulatory decision-making. However, in order to prevent any undue regulatory bias

in the results, experts from other areas, such as academia were also identified. This was achieved by using 'snowball sampling' where those people who had already taken part in the research were asked to suggest others who may agree to participate (Smith, 1975: p118; Dane, 1990: p161). These other experts participated in the research to a lesser degree than the principal expert, i.e. they may have taken part in one or two of the knowledge acquisition methodologies used, but they were not 'lesser experts' in terms of their particular expertise.

Following an examination of the literature, 'experts' in the context of this research were determined to have several attributes based on their knowledge, their acceptability as experts by their peer group and their willingness to take part in the research. These attributes were:

*Knowledge*

- At least ten years experience in the field of groundwater protection and pollution prevention
- Familiarity with the groundwater protection regulatory framework in England and Wales

*Peer Acceptability*

- Be considered by their peer group as an 'expert' in the field (at a national level)

*Co-operation*

- Willing to articulate their problem-solving strategies verbally and on paper
- Willing to discuss and explain their decision-making processes in detail
- Willing to set aside time for meetings and elicitation sessions

Although the ideal situation is to identify someone with all the attributes listed above, especially in the case of the principal expert, this is not always possible. However, compromise is possible and the last two criteria were considered most important for this research. This was due to the considerable amount of time required (sessions lasting at least one hour, over a period of several months) in terms of interviews and other knowledge acquisition sessions from each person but in particular for the principal expert. If someone is willing and able to co-operate in the research but they only have eight years experience, this should not discount them from taking part.

*Maintaining Interest and Support*

Having identified someone who met the criteria listed above (or as close to it as possible) and who could act as a principal expert, an initial meeting was arranged. This consisted of a short 'tutorial session', where the aims and objectives of the work were explained and some preliminary information was given about knowledge systems and their use. A short written report was also prepared and given to the principal expert (giving more detail of the work). At this stage, the principal expert was asked to suggest others who would be suitable to participate in the research and most importantly may also be willing to take part. These other people were approached separately but it was indicated that the principal expert had suggested their name.

Meetings with all participants were always pre-arranged, and the session structure and the aims and objectives of the research explained, in advance. An important point when arranging and running such a session is to give an accurate indication of how long it will last. This is important for two reasons. Firstly, the person who agrees to participate will need to arrange time in their diary, and secondly, if an inaccurate length of time is given, the session may be curtailed by the participant. Curtailment of a session can be critical as many of the methodologies used in this research, such as concept sorting, are time consuming and cannot be completed successfully in less than one hour.

Maintaining the co-operation of the principal expert is a crucial part of the knowledge acquisition phase as they must take part in multiple sessions. Co-operation was encouraged in several ways. At the beginning of each session, an update on progress with system development was given. The system software was demonstrated using a simple example knowledge system based on a familiar problem of 'why your car will not start' and a small system comprising less than ten rules in the area of groundwater protection was also demonstrated. By using demonstration systems the expert can be involved fully with the research and understand what progress is being made and why they are being asked to take part in certain, potentially unfamiliar, exercises.

### **7.1.3 Identification of Potential System Users and Their Requirements**

Identification of potential system users is a key element of successful knowledge system design. A system developed without the input of the potential system users is less likely to be successful (e.g. Kidd, 1985; Roberts, 1990; Berry, 1994). Potential users were identified from the regulatory environment, as inexperienced risk assessors and non-specialist groundwater officers. They would, however, be able to understand how groundwater becomes polluted, potential sources of that pollution and how pollutants could move through soil etc. to affect groundwater. People with these type of skills included water quality officers and waste regulation officers. Potential users in industry, who may have responsibility for groundwater protection, such as environmental managers, were also identified. Users were identified by, for example, asking the principal expert to suggest managers who would be supportive of the research and willing to allow staff time to take part in interview sessions. This is similar to the method utilised for identifying suitable experts, i.e., snowball sampling (Smith, 1975: p118; Dane, 1990: p161).

A total of 25 potential users contributed from a variety of sources including the Southern, Severn Trent and North West of what were the National River Authority (NRA) regions of the country, a waste regulation authority, two local authorities and industry. Potential users from more than one region of the NRA (now the Environment Agency) were asked to contribute to minimise the introduction of bias from any one region. A full list of all those who have taken part in this research is given in Appendix D.

In general, users were not approached directly, their line management being contacted initially. As each participant was required to spend approximately one hour away from normal work duties, it was vital to ensure that managers gave permission for this. Following line management agreement a formal invitation was sent to users informing them of what was required, i.e. completion of a short questionnaire and a semi-structured interview lasting approximately 45 minutes. An information sheet about the research was included. The questionnaire was designed to be completed before the interview and then to be discussed as part of the latter. The questionnaire and information sheet are included in Appendix A.

Interviews took place face-to-face and in isolation from other colleagues (to avoid noise distractions etc.) Although each interviewee knew that the session would last for approximately 45 minutes many showed great enthusiasm for the project and stayed beyond one hour. Care was taken to ensure that those taking part were aware of why they were being interviewed (e.g. presentation of a project information sheet to each participant) and each interview began with a short introduction to the project and the participant's input to the work. All participants were also assured that confidentiality would be respected. Due to the nature of the discussion and the relative inexperience of some of those who took part, it was decided not to tape record these interviews. Full notes, however, were taken and transcripts produced. Users were asked about:

- their academic backgrounds
- length of experience
- their job responsibilities
- the information sources they used when fulfilling those responsibilities
- their level of familiarity with computers

They were also asked about their attitudes towards using computers at work and what they would require of a computerised decision-support system if one was introduced into their workplace. Chapter 8, section 8.1.3, discusses the results of this user identification and requirements study.

## **7.2 STAGE 2 - THE KNOWLEDGE ACQUISITION PROCESS AND MODEL DEVELOPMENT**

Knowledge acquisition is often a lengthy and complex process. There are a number of elicitation techniques available to aid system development (discussed in Chapter 6, section 6.2). Although the interview is still the most prevalent technique, the use of multiple acquisition techniques is advocated in order to enrich the process and reduce bias in the results as much as possible. The use of multiple methods as a research strategy is sometimes called 'triangulation'. Triangulation has been defined as "the combination of methodologies in the study of the same phenomenon" and is used to check the validity of any findings, resulting in greater confidence in the outcome (Jick, 1979; Gill & Johnson, 1991: p150). Each technique used for this research was chosen to elicit different information, but taken as a whole the results would provide a

good model of expert knowledge for this particular application of point-source hydrocarbon groundwater pollution. The following techniques were used:

- Repertory grid analysis - used to identify potential sources of groundwater pollution and how different sources were related (by the principal expert)
- Semi-structured interviews - used to gain an overview of the area of groundwater pollution and more specifically hydrocarbon groundwater pollution by discussion of previously identified topics
- Protocol analysis - used to identify the order of the decision-making process by utilising actual case studies where groundwater has been impacted
- Concept sorting - used to investigate relationships between concepts specific to hydrocarbon groundwater pollution by utilising information gained by other methods to generate a list of concept words
- Risk rating exercise - used to obtain specific ratings based on expert knowledge in an attempt to semi-quantify some of those relationships already identified, particularly from the concept sorting technique

A search of paper-based information sources was also carried out. These included: books; journal papers; Environment Agency policy documents; standards/guidelines; data from Environment Agency databases, and information used by other countries for groundwater protection e.g., United States Environmental Protection Agency (USEPA).

### **7.2.1 Repertory Grid Analysis**

Repertory grid analysis is considered an exploratory technique and is not intended to provide the 'final answer' to questions. It can be used to provide an overview of a problem area from one person's particular point of view. The results of a repertory grid analysis are highly specific to the person who elicited the grid, another person would have a different 'view'. As the final system aims to model expert knowledge and in particular, knowledge of the principal expert, the technique was attempted with that expert. The technique was detailed in Chapter 6, section 6.2.3.

At the beginning of the session with the principal expert, 'repertory grid analysis' was explained briefly and an example of 'how you see other people' used to demonstrate the technique. A series of people were identified by the expert, such as:

- yourself
- a boss
- a successful person you know well
- a happy person etc.

On reaching about ten people (and the initials of each having been noted), the expert was asked to consider three of the people and describe why two were the same and the other one different.



For example comparing a boss, a successful person and a happy person; the last two may be well liked by work colleagues but the first may not (a construct and a contrast).

Once the expert understood what they were being asked to do they were then asked to think about possible point-sources of groundwater pollution (not necessarily all hydrocarbon related) and describe 'out-loud' those possible sources. As the expert described these point sources, each separate point-source (or element) was then written onto a piece of card (10cm x 10cm) and the card numbered. The expert was then asked why one element (point-source) was different to the others, with the elements presented in threes. The elements were presented systematically, i.e. cards 1,2,3 then 4,5,6 etc. The difference between the three elements (why two are alike and one is different) is termed a construct, which must be bipolar, e.g. heavy/light, high risk to groundwater/low risk to groundwater. It was made clear to the expert that there was no limit to the number of point-sources or to the number of constructs that could be generated.

The second stage involved construction of a grid with the two opposing terms of the construct in the left and right hand columns and the elements listed along the top of the grid between these opposing terms. Each element (pollution point-source) was then rated by the expert on an ordinal scale of 1 to 5 (low to high) for each construct. The construct 'risk to groundwater' example below (Table 7.1) shows a chemical factory rated higher than a landfill, and the lowest rating is applied to an oil tank.

When rating elements for a construct, at least one must be rated 1 and at least one must be rated 5. All other elements can be rated anywhere on the scale of 1-5. The process of rating all elements against all constructs continued until the grid was completed and in this case this took approximately two hours (using ten elements). The grid was then analysed and as the grid was elicited used an ordinal rating scale, a cluster analysis could be carried out (Chapter 6, section 6.2.3) to identify differences and similarities between the elements and constructs identified by the expert.

**Table 7.1:** Grid construction - elements and constructs

Construct	Elements				Construct
	Landfill	Heating oil tank	Petrol station	Chemical factory	
Low risk to groundwater	4	1	3	5	High risk to groundwater

### 7.2.2 Interviews

Interviewing of experts is often a major component of the knowledge acquisition process (Chapter 6, section 6.2.2). Interviews can be used to provide an overview of the problem area, as in 'fact finding interviews' (Price *et al.*, 1995). The technique can also be used as a 'tutorial session' where the expert tutors the knowledge engineer in a particular problem. In the context

of this research the principal expert was akin to the 'key informant' used in ethnographic interviewing (Le Compte & Preissle, 1993: p166).

A semi-structured interview format was utilised for all interviews (nearly all acquisition sessions had some interview element to them, but four main interview sessions were carried out with the principal expert). This format was used to maintain flexibility to allow an overview of the area to be obtained but also to allow more direct probing of a topic. Topics for discussion with the principal expert were initially identified from paper-based information sources such as the NRA Policy and Practice for the Protection of Groundwater (NRA, 1992). Topics for subsequent sessions were identified from previous sessions and interviews carried out with other participants. Some of the topics identified for discussion during the first interview with the principal expert are shown below:

- groundwater and its importance in England and Wales
- sources of groundwater pollution in general
- specific sources of groundwater pollution such as hydrocarbons
- who is responsible for groundwater protection within the organisation
- what is the decision-making process when groundwater pollution is suspected
- who makes these decisions
- initial system layout
- why these topics are being discussed (i.e. to model expert knowledge on hydrocarbon groundwater pollution, the expert decision-making process and how the concept of risk is incorporated into this process)

These topic areas were identified before the interview session and a basic protocol devised to provide direction during the interview. The questioning strategy adopted focused on open, probing questions (discussed in section 6.2.2) without repeatedly asking the principal expert (or other participants) 'how do you do that'.

Interviews ranged in length from approximately one hour to two and a half hours and were carried out at the participant's workplace or at the university. Where possible the interview was tape-recorded and detailed notes of the session were also taken. A series of interviews were carried out with the principal expert (a regulatory groundwater specialist) and single sessions with other participants. This was because the principal expert, as the main participant, provided more information (too much to elicit in one session) and subsequent sessions were used to check information obtained from previous sessions.

### **7.2.3 Protocol Analysis**

The technique of protocol analysis can be used to gather information on 'typical' events, where the expert is asked to 'think aloud' as they solve a problem (Chapter 6, section 6.2.2). Protocols can be undertaken in different ways such as observing the expert problem-solving as part of

their normal day-to-day activities (on-the-job protocol analysis) or the 'off-the-job' protocol analysis, where the expert can be asked to solve a problem as though they were carrying out their work duties. Off-the-job protocol analysis was used so that case studies (prepared before the session) could be used to focus attention on specific sources of groundwater pollution and to keep the amount of time necessary to run the session to a minimum (on-the-job observations can take days to obtain sufficient information on the particular aspect of expertise that is being modelled). The technique is time consuming both for the expert and for those observing and recording the process, therefore it was only used with the principal expert, which is recognised as a potential limitation of the research. However, the results of this session were used as a basis of the 'chronology of actions' for the prototype knowledge system which was evaluated by other participants.

The principal expert was presented with the problem scenario and told that there was specific site information available on request. An example case study is given in Appendix B.1. The type of information available included:

- information on site geology
- information on site hydrogeology
- type of key pollutants released at the site
- brief details of potential targets in the vicinity
- schematic site plan
- key results of monitoring and previous investigations (if available)

The amount of information given to the expert was kept to a minimum but extra information was provided if requested. The type of information requested and when it is requested is useful when trying to model a decision-making process.

All the example problems were based on actual sites. The example problems included a significant element of potential groundwater pollution from a variety of potential contaminants including hydrocarbons. The three cases presented to the principal expert were as follows:

- (i) Petrol-filling station - representing the smaller source with potential to release relatively well-defined pollutants such as petroleum but with a large number of potential sources, relatively recently identified as point-sources of groundwater pollution;
- (ii) Landfill site - perceived to be major sources of point-source groundwater pollution, relatively well investigated and regulated; and
- (iii) Industrial site - also perceived to be major sources of point-source groundwater pollution but with actual known pollution of an abstraction borehole with chlorinated solvents.

The principal expert was asked to read the information supplied and detail 'out-loud' how they would assess the sites in each case. Notes were taken for each of the expert assessments, paying particular attention to the 'chronology of actions' the expert described.

## 7.2.4 Concept Sorting

Concept sorting is a method for identifying key terms that are perceived to relate to the problem being studied and the interrelation of these terms (Chapter 6, section 6.2.3).

During one of the interviews carried out with the principal expert, they were asked to describe some general, non-site specific, point-source problem scenarios that could impact on groundwater (not necessarily related exclusively to hydrocarbon pollution). From the interview transcript, concept words were elicited that described the subject of groundwater pollution and point-source hydrocarbon pollution in particular. Eighty concepts were elicited. After the initial compilation of concepts from the interview data, the principal expert was asked at a subsequent elicitation session to check and confirm that they were satisfied with the listing.

After this stage, each concept word was typed onto a piece of card (the size of a playing card) and a unique identifying number printed on the reverse (for recording purposes). At the next elicitation session with the principal expert, concept sorting as an elicitation technique was explained. Before sorting the concept words that related to the area of groundwater pollution and protection, the expert was shown possible ways of concept sorting with an artificial domain - an artificial domain being a simple and less complicated problem area (Shadbolt & Burton, 1995). The example used is shown below.

Concept sorting was demonstrated by sorting these artificial domain concept words into two categories:

- (i) 'birds' and 'non-birds' and
- (ii) 'animals' and 'plants'

**Table 7.2:** Concept words for illustrating the technique of concept sorting

Card No.	Concept Word	Card No.	Concept Word
1	Cod	11	Sparrow
2	Dog	12	Daffodil
3	Grey seal	13	Mackerel
4	Hedgehog	14	Thrush
5	Kelp	15	Willow
6	Oak tree	16	Sea bass
7	Snake	17	Daisy
8	Skua	18	Sea otter
9	Beech tree	19	Blackbird
10	Frog	20	Guillemot

After this demonstration the expert was asked to sort the concept words relating to groundwater pollution and protection. The cards were shuffled and the expert was asked to sort these cards into various categories (piles) that the expert devised (such as 'high and low risk to groundwater'). If a concept word was not understood by the expert an explanation was provided to enable the card to be placed in an appropriate category. If a particular concept

word was considered irrelevant and could not be categorised, a separate category was created for these terms.

The number of the card and the category in which it was placed was recorded. The sorting process was repeated as many times as the expert could generate new categories, the position of each card being recorded separately for each sort. It was made clear to the expert that there was no limit to the number of sort categories that could be devised or what they could be. The sort categories or labels used by the principal expert were also recorded.

The sort categories and concept cards devised by the principal expert were then presented to other Environment Agency staff, environmental managers in industry and academics and a similar sort procedure repeated with each. Apart from one academic participant, these other participants were not considered 'expert' in groundwater protection and were asked to take part to identify any differences with the principal expert. The academic expert was utilised to identify any difference between a regulatory and an academic approach to the problem of groundwater protection. The academic expert was not considered as the principal expert as the system was primarily aimed at a regulatory user group.

### **7.2.5 Risk Rating Exercise**

This method allows an expert to give an estimate of the 'relatedness' between different factors (Chapter 6, section 6.2.3). This risk-rating exercise was carried out by the principal expert, a regulator, an academic and by two industry representatives. The type of rating scale used for this research (similar to a Q-sort scale) is difficult to conduct with many respondents and is usually only carried out with a small group, sometimes only one person. This can introduce problems of bias and reproducibility. However, it is a very useful exploratory technique even with these limitations (Dane, 1990: p282).

Various factors, relevant to the study and management of groundwater protection, were obtained using the technique of concept sorting and derived from a literature search (e.g. CCME, 1992 and HSE, 1996b). Factors were grouped broadly into source, pathway and target terms in order to simplify the rating exercise and to follow the inherent risk assessment process.

Using this source-pathway-target model, factors in either the source or pathway or target groups are interdependent in terms of the risk rating but they may overlap (e.g. groundwater can be a pathway and/or a target).

Each participant was asked to rate each factor presented to them in a series of tables in terms of groundwater protection and pollution. Three rating scores were requested for each factor under the headings of, hazard rating, information requirements and response time, which were taken directly from the results of concept sorting.

**Hazard rating:** Factors in this category were sorted into high, medium and low hazard to groundwater. For example 'benzene' as a source of pollution, could be termed a high hazard factor (because it is a highly toxic chemical) but 'clay strata' as a potential pollutant pathway, may be a low hazard factor (because it is relatively impermeable).

**Information requirements:** Factors were sorted into categories such as; (i) 'do something yourself' i.e., you have sufficient information for your personal requirements, (ii) 'more information needed' i.e., you can deal with the factor but you need more information before you can proceed, and (iii) 'pass it on to a specialist' i.e., you do not have the information to deal with the problem and you need to pass it on to be dealt with by a specialist.

**Response time:** Factors were sorted into categories such as; (i) 'do something immediately' i.e., action needs to be taken now if the problem you are dealing with is to be controlled effectively, (ii) 'longer term action' i.e., you have more time to consider your actions but something must be done, and (iii) 'no action' i.e. the factor requires no action to be taken by you.

For each category, a rating of between 1 and 5 could be allocated. Table 7.3 shows the rating scales used for each category.

**Table 7.3:** Rating scales used in the risk-rating exercise

Rating Category	Rating Scale						
<i>Hazard Rating</i>	High	5	4	3	2	1	Low
<i>Information Requirements</i>	Specialist information required	5	4	3	2	1	Minimal extra information required
<i>Response Time</i>	Rapid action required	5	4	3	2	1	Long term or no action sufficient

Each factor could be scored a minimum of 0 and a maximum of 15 by the addition of scores for each of the three categories. Table 7.4 gives an example of how a factor could be rated. This provided an approximate weighting for each factor, those with the 'highest' total score could then be identified as 'factors of key importance' and could be weighted as such in the prototype knowledge system.

If a participant felt that a factor could not be rated for any of the three categories (i.e., if that factor is irrelevant) the box was then be left blank, e.g., the factor 'Sampling regime' may not be rated for response time, so that particular box was left blank.

**Table 7.4:** An example of the combined rating for a specific factor

Factor	Hazard Rating	Information Requirements	Response Time	Total Rating Score
<i>Spillage of diesel</i>	5	1	5	11
	High hazard rating, diesel as a pollutant can present a high risk to groundwater	Minimal extra information needed about type of pollutant	Rapid response required to deal with problem	Relatively high weighting

### 7.2.6 Comparison of Knowledge Acquisition Techniques Used

From observations made during this research and by others (e.g. Welbank, 1983; Neale, 1988; Neale & Morris, 1988; Cooke, 1994; Hoffman *et al.*, 1995) it is concluded that some techniques are more effective than others in accessing the information required. The disadvantages and advantages of the techniques used are summarised in Table 7.5.

Repertory grid analysis was found to be time consuming both at the stage of construct identification with the expert and later at the analysis stage. As a technique it does, however, provide an overview of the problem area as the expert perceives it, enabling similarities and differences to be identified between different types of point-source. For example, a petrol-filling station compared to a major chemical factory present a different risk to groundwater as potential point-sources of pollution. Repertory grid analysis has been suggested for use in the knowledge acquisition process for knowledge system development by several authors, most notably Shaw and Gaines (1987a and 1987b) who used automated techniques to gather the information and analyse it. The use of automated repertory grid analysis would perhaps reduce the time needed to elicit and analyse the information.

Semi-structured interviewing was used at several different sessions and sometimes combined with another technique: for example, the session began with a semi-structured interview but then moved on to a concept sorting session. Interviews with the principal expert were used initially to gather background information but subsequently to ask specific questions about a topic. The interview protocol was important in ensuring that direction was maintained during the interview and all points were discussed. Interviews, although they are often time consuming and can produce long transcripts, provided invaluable information and opportunities to question the principal expert in detail.

Protocol analysis is discussed by many authors as a useful technique in the knowledge acquisition process (e.g. Welbank, 1983; Ericsson & Simon, 1984; Shadbolt & Burton, 1995) but is acknowledged to be time consuming on the part of the expert and those analysing the results. It is a good technique for studying what happens on a day-to-day basis if used 'on-the-job' i.e., observing the expert as they go about their normal problem solving activities.

However, this type of observation is not always possible as several days may be required before sufficient information is gathered, so 'off-the-job' protocol analysis was used for this research. This gives the expert, opportunity to solve 'problems' (represented by case studies) as close to 'real' time as possible but allows the expert to focus on the case studies of interest to this research. Both types of protocol analysis give useful information on the order of the decision-making process and what type of information is used and when.

**Table 7.5:** Comparison of knowledge elicitation techniques utilised during this research - advantages and disadvantages

<b>Elicitation Technique</b>	<b>Advantages of the Technique</b>	<b>Disadvantages of the Technique</b>
<i>Repertory Grid Analysis</i>	<ul style="list-style-type: none"> <li>• Able to get an overview of a problem area</li> <li>• Uncover relationships that the expert has not articulated</li> </ul>	<ul style="list-style-type: none"> <li>• Contrived technique not natural to the expert</li> <li>• Difficult to analyse effectively with more than ten elements</li> </ul>
<i>Interviews (semi-structured)</i>	<ul style="list-style-type: none"> <li>• Able to gather background information</li> <li>• Can take account of rare events</li> <li>• Familiar to the expert</li> </ul>	<ul style="list-style-type: none"> <li>• Long transcripts for analysis</li> <li>• May focus on 'non-typical' or rare events to detriment of typical events</li> <li>• Can get 'off the point'</li> </ul>
<i>Protocol Analysis</i>	<ul style="list-style-type: none"> <li>• More natural to the expert</li> <li>• Can study 'typical events'</li> </ul>	<ul style="list-style-type: none"> <li>• Expert may feel under pressure, their expertise is being 'questioned'</li> <li>• Can generate lengthy transcripts</li> <li>• Very time consuming if 'on the job' or shadowing expert, slightly less so with 'off-the-job'</li> </ul>
<i>Concept Sorting</i>	<ul style="list-style-type: none"> <li>• Identification of relationships between concepts</li> <li>• Relatively quick, can be repeated many times</li> <li>• Can be used to generate rules directly</li> </ul>	<ul style="list-style-type: none"> <li>• Contrived technique not natural to the expert</li> <li>• May prove irritating to the expert</li> <li>• Requires some expertise to complete properly</li> </ul>
<i>Risk-Rating</i>	<ul style="list-style-type: none"> <li>• Able to apply a 'scale' to the results</li> <li>• Large number of concepts can be rated</li> </ul>	<ul style="list-style-type: none"> <li>• Possibility of mis-interpreting scales</li> <li>• Requires considerable expertise to complete properly</li> <li>• Only possible with a small group of participants</li> </ul>
<i>Literature Search</i>	<ul style="list-style-type: none"> <li>• Many different types of source</li> <li>• Sources generally relatively easy to access</li> <li>• Tremendous amount of information available</li> </ul>	<ul style="list-style-type: none"> <li>• Variety in quality of information</li> <li>• Mis-interpretation of the information</li> <li>• Out of date information</li> <li>• Difficulties in identifying required information</li> </ul>

Concept sorting is a contrived technique that requires a full explanation to the participants before a session begins, otherwise it can appear to the participant to be a worthless activity. It is also important to ensure that those who are asked to participate in a concept sorting session have sufficient knowledge of the problem area to complete the task. The results will be meaningless if the participant is forced to 'guess' what is required. However, it is an effective technique when used to identify terms that are specific to the problem area and how those terms



are related. It can also be used to compare subjectively, the principal expert and other participants to assess the level of agreement with the principal expert.

Risk-rating as used during this research was directly built upon the results of the concept sorting exercise. Similar to concept sorting, what the participant is being asked to do must be explained fully before the exercise begins and participants must have the requisite knowledge to be able to complete the task. It can be used to semi-quantify some of the relationships identified by concept sorting and give an estimate of that 'relatedness'. This type of technique is acknowledged to be difficult with a large number of participants and is really only suitable for a small group and even just one person can be used (Dane, 1990: p282). This obviously introduces problems of bias and reproducibility but by carrying out the exercise with more than one person, this can be kept to a minimum. The results obtained are not absolute values of measurement e.g., absolute measures of relatedness, they only represent a scale for comparison purposes. This is an important point, as using these results to construct an overall prioritisation scheme based on a variety of factors (as in this research) could imply some kind of absolute quantification which is in no way justified by the research methods used. The information obtained is problem-specific and provides a basis for comparison of factors and ultimately sites, when the problem is specifically related to petrol-filling stations as point-sources of petroleum hydrocarbon pollution of groundwater in the UK.

Using the literature as a source of information is the most common knowledge acquisition technique used for knowledge system development. There are many different types of source that can be used from text books to information on the World Wide Web. The literature is invaluable for providing background information but also specific information can be discussed in an interview, for example. Problems with using the literature include out of date information and information that is not widely accepted by the expert community, appearing as 'fact'. These disadvantages can be easily reduced by using at least one other acquisition technique such as interviews.

The use of multiple techniques for social science based research, although advocated by many authors (e.g. Gill & Johnson, 1991: p152) is not always followed through in practice. For example Moula, Toll and Vaptismas (1995) carried out a survey of knowledge systems in the geotechnical field and found that the majority used one or two knowledge acquisition techniques; the literature and one other (usually interviews). The choice of method is also important as the 'weight' given to the results obtained from each method (e.g. Jick, 1979). For this research a range of methods were chosen that would produce different types of information but that were also interdependent upon one another so the results from concept sorting for example could be used in the risk-rating exercise.

Deficiencies in the strategy used for this research and in the methods themselves were apparent (often with hindsight). For example the risk-rating exercise attempted to semi-quantify some of the relationships noted from results of the concept sorting, but the sample size was very small. Although the sample did include the principal expert whose expertise the knowledge system was based, it is acknowledged that an undue amount of bias may have been introduced at this point. The use of other methods such as the Delphi technique (e.g. Mostyn, 1985) would perhaps have provided more reliable results and would certainly have used a larger sample size. In general a notable deficiency with the research strategy employed for this research was the small sample sizes which was partially compensated for by using multiple methods.

### **7.3 STAGE 3 - PROTOTYPE DEVELOPMENT AND SYSTEM EVALUATION**

The final stage in system development is where the information gathered as part of the knowledge acquisition process is represented in a computer-based form. There are three key elements to this stage:

- (i) choosing a development platform;
- (ii) building the system, and
- (iii) deciding how the resulting system will be evaluated.

Elements (i) and (iii) are discussed below but the process of the building the system (ii) is discussed in detail in Chapter 9.

#### **7.3.1 Development Platform**

As discussed in section 6.1.5 (Chapter 6) knowledge systems can be developed via a programming language such as PROLOG, by use of a system shell or by using a 'structured development environment', e.g. the use of KADS (Kingston, 1995).

For this research a shell environment was considered the best development option. This decision was based on several criteria such as level of flexibility in programming required, software availability and cost. Some advantages and disadvantages of each development option are shown in Table 7.6.

There are many shells sold as commercial software and a selection of evaluation criteria was used to identify the shell for this research. Evaluation criteria can consist of questions such as (Waterman, 1986: p143; Palmer & Mar, 1988; Philip, 1991)

- What is the maturity of the software (number of years on the market)?
- What is the availability of documentation and other developer support?

- What is the training level of the person required to develop the system?
- What are the time constraints on system development?
- Does the system need to interface with other software?
- What are the graphics requirements?
- What are the user interface requirements?

Those factors chosen as evaluation criteria for this research and how the selected shell performed against those criteria are discussed in Chapter 9, section 9.3.1.

**Table 7.6:** Advantages and disadvantages of possible knowledge system development options

Development Option	Advantages	Disadvantages
<i>AI programming languages</i>	High flexibility in programming, very sophisticated systems can be developed	Relatively high cost, experienced programmer required to develop system
<i>Structured development environments</i>	Support for high resolution graphics, includes system maintenance tools, choice of reasoning strategies, highly sophisticated systems possible	Not easily available for the PC, most expensive option (£20,000+), highly complex (so require experienced developer)
<i>Shells</i>	Available for the PC, relatively low cost (few hundred pounds), simple to use, do not require an experienced programmer or developer	Lower flexibility in programming, restricted to one knowledge representation e.g. rule-based

### 7.3.2 System Evaluation

After the system has been constructed, it must be evaluated to assess if it meets the original design objectives. Although system evaluation is shown as part of stage three of the system development, it actually forms a component of all stages. Knowledge that is collected is continually being updated and incorporated into the knowledge base of the system (e.g. Figure 6.3). However, the final stage does allow an evaluation to be conducted on the prototype system. System evaluation consists of two tasks; verification and validation (Chapter 6, section 6.1.6). For the purposes of verification, the system and its rule base were presented to the principal expert for evaluation. The following checklist of 'verification' and 'validation' questions was used as a basis of the evaluation procedure:-

#### *System Verification*

- Are the rules correct, consistent and complete?
- Does the system make decisions that the expert would agree with and that are appropriate to the situation?
- Does the system 'do' things in a sensible order?
- Does it ask inappropriate questions?
- Is the explanation facility good enough to explain how and why a decision was made by the system?

- Are there problems suitable to test the system?

#### *System Validation*

- Does solving the problem actually help the user?
- Are the systems' answers presented in an understandable way and at the right level of detail?
- Is the system fast enough for the user?
- Is the user interface easy to use?

The principal expert was asked to try out the system using a representative problem that they devised, and go through the question and answer session to categorise the example site in terms of Environment Agency point-source severity. They were encouraged to identify any errors in the reasoning of the system or any areas that were difficult to follow. After this session, a report of the system showing the rule base was given to them for their written evaluation, to allow for a period of reflection and to encourage reasoned judgement.

This process was repeated with another regulatory hydrogeologist who had taken part in the knowledge acquisition phase of system development but who had a specific interest and knowledge of the area of petroleum groundwater pollution. The system was then evaluated by a regulatory hydrogeologist from a region of the Environment Agency who had not taken part in any of the development stages and who personally had not had any input to system development.

Evaluation was not only carried out by the principal expert in order to reduce any bias or errors introduced by them. The second regulatory hydrogeologist had specific knowledge of petroleum as a source of groundwater pollution (which the principal expert did not have in such detail) and had worked with the principal expert so was aware of their particular 'way of thinking'. The third hydrogeologist who had not taken part in any of the knowledge acquisition activities previous to the evaluation session and who came from a region of the Agency that had not taken part in the research, was used to provide an independent 'check' on the system.

At the validation stage, the system was presented to some potential system users (as opposed to experts). Potential users were given an example problem to solve using the system. After this evaluation session, participants were asked to complete an 'evaluation questionnaire' (shown in Appendix A.4). Six potential users took part in this evaluation session, the computer-based part of the session lasting approximately 30-45 minutes and the questionnaire taking approximately 15-20 minutes to complete.

### **7.3.3 Observations on the Evaluation Process**

The evaluation process is rightly considered an essential part of system development but is often a neglected part of the process (Lydiard, 1992; Mengshoel & Delab, 1993). It is the

knowledge that has been encoded into the system that will determine the quality of its performance (Vermesan & Meldal, 1996) but that performance must be evaluated.

Evaluation should not only be based on how many test problems the system gets correct (Stefik, 1995: p165) but questions such as does the system 'do' things in a sensible order or does it work fast enough must also be considered as part of a full verification and validation process. However, the actual process of evaluation is difficult and takes a considerable amount of time. For this research three experts were asked to evaluate the system, one of them being the principal expert who provided a large amount of information for the system. The principal expert was able to evaluate the system at many stages during development but evaluation of the completed prototype is necessary to ensure that the process is undertaken in a systematic way for the whole system. Due to the question of bias and error that could be introduced by over-reliance on the principal expert, the most 'important' expert, is the person who has had not previously contributed to the research, this gives an independent view of the system and system objectives.

A particularly useful part of the evaluation procedure used during this research was the report on the system that evaluators could take away with them and comment on after the evaluation session with the computer prototype. Comments could then be incorporated into the system and the outcome of the evaluation process implemented properly. Potential system users must also be consulted as part of the overall evaluation process to ensure its validity. Users provided their evaluation via a questionnaire which was designed to investigate user's attitudes to the system as well as practical issues such as those concerning the user interface. Attitudes to the system are important as "the chances of producing a successful system are greatly reduced if potential users do not want it" (Roberts, 1990).

Issues that were investigated included:

- System performance e.g. does the system actually help in carrying out a task?
- Information provision and interaction e.g. user instructions
- Physical issues e.g. use of a mouse rather than a keyboard
- Personal attitudes to the system e.g. is the user confident in using the system?

Although considered an essential part of this research, user evaluation sessions were difficult to run. This was mainly due to logistical problems of arranging for volunteers to come to the University to take part and some technical difficulties with the computer hardware used. It is recognised fully that the sample was small and results have only been used descriptively. However, of those who did take part, all were fully representative of the type of user for whom the system has been designed. The results of the evaluation process are discussed in more detail in Chapter 9, section 9.4.

## CHAPTER 8

### 8 SYSTEM DEVELOPMENT - KNOWLEDGE CHARACTERISATION

The system development process was described in Chapter 7 as consisting of three main phases:

- Stage 1 - Framing the problem
- Stage 2 - Knowledge acquisition and conceptual model development (conceptualisation)
- Stage 3 - Prototype development (implementation and evaluation)

These stages and how they relate together were represented in Figure 7.1 (Chapter 7). The outcome of Stages 1 and 2 is reported here, while Stage 3 is discussed in Chapter 9.

#### 8.1 STAGE 1 - FRAMING THE PROBLEM

At the beginning of Stage 1 an initial problem description was devised as a guide to progress and to enable questions related to the problem to be answered (section 8.1.1). This description did not have to be detailed as it was used merely as a base from which to start development.

##### *Initial Problem Description*

The processes of risk assessment and risk management now support environmental protection in the UK. Risk assessment can provide a systematic and structured analysis of a problem and can be particularly useful in assisting in prioritisation of management activities towards the most significant risks. Unfortunately, although risk assessment is gaining acceptance in the regulatory field it is often not applied in a consistent manner. The Environment Agency is responsible for the protection of groundwater in England and Wales and has identified that sites such as petrol-filling stations can threaten groundwater as point-sources of hydrocarbon pollution. There are a large number of active sites and a legacy of closed/redeveloped sites all over the country. The Environment Agency as a body has limited resources in terms of time, money and expertise. The use of a knowledge system could act as a decision-support tool to assist non-specialist regulatory personnel to prioritise risks and risk management activities relating to groundwater threats from hydrocarbon point-sources such as petrol-filling stations (Butler & Petts, 1997).

This initial problem description was then used to further characterise and define the problem area as a whole.

### 8.1.1 Problem Characteristics and Definition

During the first stage of development the questions listed in Table 6.1 (Chapter 6) were addressed and details are given below. Although these questions are presented in a particular order, in practice all question areas must be satisfactorily assessed before moving on to the next stage of development, however, the order in which this is carried out is not critical.

- *Is knowledge system development possible?* Several authors (e.g. Waterman, 1986: p129, Hushon, 1989a; Crowe, 1994) considered that there were certain key requirements necessary for knowledge system development to be possible and these are considered below.
  - The problem area is not too difficult and is relatively well understood - this is a difficult point to prove or disprove and should be considered in terms of system development rather than whether the field of groundwater pollution is a 'difficult' area intellectually. The prioritising of petrol-filling stations using a risk-based approach is possible and the problem characteristics are relatively well understood by the experts as they are able to articulate them (section 7.2).
  - The problem occurs often - the need to be able to identify and prioritise sites such as petrol-filling stations in terms of their risk to groundwater is a national problem. There are nearly 15,000 active sites in the UK and a historical legacy of 'ex-petrol stations'. This type of point-source has been identified in the latest survey by the Environment Agency as having a considerable impact on the groundwater environment (de Hénaut *et al.*, 1997).
  - A solution to the problem requires expert judgement and interpretation as well as factual knowledge - the prioritisation of sites such as petrol-filling stations in terms of risk to groundwater does require expert judgement. Non-experts or those with less experience in the area do not perform so well in tasks that require specific expert knowledge (e.g. section 7.2.4).
  - A human expert exists who can articulate their methods and experts agree on the solutions - human experts in the field of groundwater protection do exist and the basic parameters of the field are agreed upon (identification of an expert etc. is discussed in more detail in section 8.1.2).
  - There should be a sufficient number of case studies to enable any knowledge system developed to be verified - there are several accounts of petroleum hydrocarbons impacting on groundwater in the UK and elsewhere (detailed further in Chapter 9, section 9.4).
  - The problem solution requires consistency of response even when data input varies in quantity and quality - 'consistency of approach' is one of the main aims of the Environment Agency in carrying out its duties and it is recognised that

information can vary in quality and quantity making a knowledge-based approach advantageous.

- ♦ The use of a knowledge-based approach must be more effective than alternative methods - this is difficult to prove or disprove without developing and comparing both a paper-based scheme and a non-knowledge-based computer system. However, the literature supports the use of knowledge systems (sections 5.2 and 5.3) over more conventional methods as they are user-centred. The results of the user evaluation process for this research are detailed in Chapter 9, section 9.4.
  
- *Is knowledge system development justified?* - there are several possible justifications for developing a knowledge system (shown in Figure 5.7, Chapter 5). The most pertinent to this research are that 'Human expertise is rare' and 'Expertise is needed in many locations'. Although there are experts available in the area of groundwater pollution and protection in the UK, they are relatively rare and are not always available to the regulatory staff who may need to consult them. That expertise is needed in many locations is demonstrated by the fact that hydrocarbon point-source groundwater pollution is a national problem, as is the regulatory infrastructure set up to deal with it. The forthcoming changes to the way contaminated land is identified and assessed in England and Wales (Department of the Environment, 1996b) will also place a greater responsibility on Local Authority staff such as environmental health officers, whose main area of expertise is not likely to be in contaminated land or groundwater protection (potential system users are discussed further in section 8.1.3).
  
- *Is knowledge system development appropriate?* - the nature, complexity and scope of the problem area has an effect on whether knowledge system development is appropriate or not (Figure 5.8, Chapter 5). Again, these problem characteristics should be examined in the context of actual system development and not just the cognitive requirements of the subject.
  - ♦ Nature - the problem must require symbol or concept manipulation and not be solved by mathematical reasoning alone (i.e. requires heuristic knowledge). This is clearly the case when assessing a site and the risk to groundwater. The very nature of 'risk' is such that there is always uncertainty in assessments.
  - ♦ Complexity - this is difficult to represent in words but the problem solution should not be 'too easy' and should require several years of experience before someone could be considered an 'expert'. In the field of regulatory groundwater pollution and protection (e.g. Environment Agency) staff are generally qualified to first degree level and often to postgraduate level and require years (often many) of experience before reaching positions of responsibility acquiring recognition as an 'expert'.



- ♦ **Scope** - the problem must be manageable in terms of knowledge system development. If the problem area is defined too widely, knowledge acquisition and rule-base development becomes technically impossible. A system developed for a particular set of users (regulators) to support decision-making around one set of contaminants (petroleum hydrocarbons) is manageable but also retains its practical application.
- *Who are the potential users of the system?* - this question is addressed in section 8.1.3
- *Who are the experts in the problem area?* - this question is addressed in section 8.1.2
- *What are the problem boundaries?* - this is in essence the same question as that posed when the problem area was assessed as being appropriate for knowledge system development. The scope of the problem must be manageable. By restricting the system to one set of contaminants from one type of point-source, risk to groundwater can be assessed.
- *What is the language of the problem area?* - this is an important consideration particularly with technical problem areas, as words can be used with different meanings from their everyday usage or usage in other applications. A relevant example to this research are the terms 'risk assessment' and 'risk management' which have a variety of meanings to different 'risk communities'. Even the word 'risk' itself can have several different meanings. This was specifically discussed in Chapter 2, section 2.1.3. For successful system development an awareness of what each term means in context must be accounted for in any prototype developed.
- *Are there any relevant paper-based information sources e.g., textbooks?* - there is a vast literature on groundwater, groundwater pollution, risk management and knowledge systems with relevant textbooks in each area. Textbooks are seen as "idealised knowledge" (Neale, 1988) and can provide a general understanding of the problem area. Paper-based resources used in this way for this research included: Freeze and Cherry (1979); Mumma (1995); Environment Agency (1996b); HSE (1996b); Price (1996); Petts, Cairney and Smith (1997) and Environment Agency (1998).
- *What hardware and software is available?* - this question was addressed in Chapter 7, section 7.3.
- *Has any similar research been reported in the literature?* - as part of this research a full literature review was carried out. Knowledge systems have been developed for use in

the environmental field and some relate specifically to groundwater and groundwater protection. Section 5.3 of Chapter 5 addressed this question directly.

As part of Stage 1 and moving into Stage 2 of system development, information was structured under the following framework (Grover, as referenced by Welbank, 1983: p9).

- A general problem description - the initial problem description (shown at the beginning of this chapter) was confirmed with a series of interviews, carried out at the start of the research with the principal expert (section 8.2.2)
- A bibliography of reference documents - a full literature search was carried out and the system developed includes references where appropriate
- A glossary of terms - a glossary of terms is included at the front of this thesis
- A list of experts in the field - a list of those who have taken part (where appropriate) in this research is included as Appendix D
- Descriptions of typical case studies or reasoning scenarios - these were obtained by interview and some were subsequently used as part of the protocol analysis phase (detailed in section 8.2.3)

Two particular areas of Stage 1 were considered most important to this research; identification and co-operation of an expert, and identification of potential system users and their requirements. The following two sections discuss these areas in more detail.

### **8.1.2 Identification and Co-operation of an Expert**

As discussed in section 7.1.2 (Chapter 7) a set of selection criteria were used to identify experts in the context of this research and in particular a 'principal expert' was identified from the Environment Agency (at that time the principal expert was employed by the NRA, a predecessor body of the Agency). The criteria related to knowledge, peer acceptability and co-operation.

The person identified complied with each of the specified criteria, the most important being a willingness to explain their decision-making processes and to set aside time for elicitation sessions. They were an ideal 'key informant' (Le Compte & Preissle, 1993: p166). The success of this research and the actual development of a prototype knowledge system is due in a large part to the principal expert. The principal expert is a senior manager in the Midlands Region of the Environment Agency and is responsible for the National Groundwater and Contaminated Land Centre.

During the first session with the principal expert, they were asked to suggest others who might be able to take part in the research (snowball sampling) and this led to approaches being made

to a senior academic hydrogeologist, then at the University of Bradford and other colleagues from the Environment Agency (all those who took part are listed in Appendix D). The principal expert also assisted in the identification of potential system users (section 8.1.3).

### **8.1.3 Identification of Potential System Users and Their Requirements**

#### *User Profiles*

Users were also selected using a set of criteria such as non-expert risk assessors, non-specialist groundwater staff. A total of 25 people took part in this research as potential system users, the majority of whom were regulators from the Environment Agency and its predecessor bodies, 7 people were not from the Environment Agency.

Backgrounds varied widely and included; environmental science, biology, microbiology, chemistry, geology, hydrogeology, geography and engineering. Environmental science was the most common background (30% of respondents). Nearly all were educated to first degree level and experience varied from a few months to 12 years. In no case was groundwater protection their sole responsibility and job functions included: water quality; hydrogeologist; pollution control; waste liaison; planning; commercial services; environmental health; contaminated land and environmental consultant.

The types of tasks carried out by the respondents were extremely varied. The most common, however, were:

- site inspection/monitoring tasks
- assessing various types of licence/permit applications under a variety of legislation e.g., waste management licences
- responding to pollution incidents

All these tasks require technical expertise and competent decision-making. Although some decisions were clearly made on a 'risk basis' (e.g. requesting additional conditions on a landfill waste management licence to be more protective of the groundwater environment) risk-based decision-making was not acknowledged as taking place *per se*.

The majority of people had been on some kind of training course related to their job, but most reported that they learnt how to carry out tasks 'on-the-job' and by observation of more experienced colleagues. Many respondents used colleagues as sources of information especially when a decision was required quickly. Many felt that they were asked to make decisions with incomplete or poor quality information which sometimes led to inadequate decision-making. Of those who had to be 'on-call' as regulators, nearly all felt it was difficult to

deal with such situations as there was a limited pool of more experienced people to approach for help.

Sources of information reported as being used was relatively consistent with 100% using legislation and maps, 91% using policy/guidance documents and textbooks and 70% using academic journals. Other sources of information specifically mentioned included 'colleagues', other organisations and the Internet. Only one person did not use a computer at work, with 73% using one regularly throughout the day, 9% - once or twice a day and 18% - once or twice a week. The most frequent reason for using a computer was to access an information database (100%) followed by word-processing (86%) and then for graphics use (46%). Other computer-based uses included modelling and e-mail. All respondents were comfortable using a computer as part of their job, especially if using it made them more effective.

### *User Requirements*

Users were asked about their requirements of a computer-based decision-support system that would help them prioritise sites on the basis of risk to groundwater, using petrol-filling stations and underground storage tanks as an example. Not all respondents would be required to carry out such an assessment as part of their current function.

Requirements can be separated into 'computer-based issues' (a function of using computer software as opposed to paper-based schemes) and 'technical issues' (what information a system would require and what type of tasks the system would need to carry out). The following were identified:

#### *Computer-based issues*

- The system must be easy to use
- The system must be easy to understand
- Good on-line help and user instructions (manuals) must be available
- Data input must be kept to a minimum
- Explanations of what the system is doing must be provided where necessary
- Ability to print off a report of the results obtained

#### *Technical issues*

- Assessments carried out by the system must be open to scrutiny (no 'black-box' programs)
- Decision-making process must be clear and systematic
- Information on sources of pollution should be included - types of pollutant etc.

- Information on ground conditions should be included - geology, depth of unsaturated zone etc.
- Information on potential targets
- Information on current legislation
- Sources of further information
- Ability to use the system to test hypothetical scenarios e.g., changing site engineering requirements

Although not all those who participated were confident computer users, all felt that development of a knowledge system to assist them in their decision-making was a good concept. An overall requirement stated by almost all participants was the need for relevant information to be available to them and the use of a knowledge system is an excellent way of supplying information.

The next stage of development was the knowledge acquisition phase which was guided by the results of the user requirements study and preliminary discussions with the principal expert. The results obtained from each technique utilised during this research are discussed separately below but Chapter 9 discusses conceptual model development and the actual building of the system: i.e. how the knowledge has been used to develop the system.

## 8.2 STAGE 2 - MODEL DEVELOPMENT AND THE KNOWLEDGE ACQUISITION PROCESS

### 8.2.1 Repertory Grid Analysis

The methodology for this technique was described in Chapter 7, section 7.2.1. The grid is formed from constructs and elements. Elements elicited for this repertory grid were potential point-sources of groundwater pollution (although not necessarily related to hydrocarbons). Ten elements were elicited from the principal expert and these are shown in Table 8.1. In total, eighteen constructs were elicited and each element was rated on a scale of 1 to 5. These bipolar constructs are shown in Table 8.2.

**Table 8.1:** Elements elicited from the principal expert for repertory grid analysis

Element No.	Elements used in the grid
E1	Major chemical factory on the Sherwood Sandstone aquifer
E2	Domestic central heating tank failure
E3	Road accident involving tanker spillage - chemicals
E4	Landfill site in opencast coal pit
E5	Redevelopment of steelworks in the Black Country, West Midlands
E6	Leakage from petrol station in Solihull, West Midlands
E7	Pulverised Fuel Ash (PFA) disposal into gravel pit - River Trent, East Midlands
E8	Soakaway system from housing estate
E9	Effluent discharge to soakaway from an animal renderers situated on chalk geology
E10	Sewage sludge spreading in an area of chalk geology

Once the grid has been constructed it can be analysed to identify relationships and patterns between the elements and constructs. The method used was cluster analysis and followed the methodology of Hart (1986). Cluster analysis compares elements and constructs. A measure of difference between two objects (elements or constructs) is defined and then objects are organised into clusters so that objects in the same cluster are more similar than those in other clusters. Cluster analysis can be used to 'focus' a grid (rearrange constructs and elements so those that are similar appear together).

**Table 8.2:** Bipolar constructs elicited from the principal expert for repertory grid analysis

Construct No.	Bipolar Construct	
	<i>First pole (rated 1)</i>	<i>Second pole (rated 5)</i>
C1	Complex, unknown behaviour (industrial chemicals)	Simple, well-known behaviour (e.g., hydrocarbons)
C2	Medium (or higher) risk to groundwater	Low risk to groundwater
C3	Groundwater is target	Groundwater is pathway (not target)
C4	Source term similar (organic)	Source term is not similar (inorganic)
C5	Potential small-scale impact on groundwater	Potential large-scale impact on groundwater
C6	Definite impact on groundwater	Not a definite impact on groundwater
C7	High risk to groundwater	Medium (or below) risk to groundwater
C8	Hydrocarbons	Non-hydrocarbons
C9	Known pollutant load	Unknown pollutant load
C10	Acute pollution	Chronic pollution
C11	Release below soil surface	Release above soil surface
C12	Long-term impact	Short-term impact
C13	Industrial situation	Domestic situation
C14	No public access	Full public access
C15	Non-microbiological impact	Microbiological impact
C16	Solid waste disposal	Non-solid waste disposal
C17	No planning legislation involved	Planning legislation controls situation
C18	Overall risk to groundwater is high	Overall risk to groundwater is low

So that objects can be clustered, the measurement of the difference or distance between them must be defined (for each construct). The distance measurement was defined as the sum of the absolute values of the differences between ratings: e.g. comparing a major chemical factory on the Sherwood Sandstone aquifer (E1) and a domestic heating tank (E2)(Table 8.1) the following ratings were obtained from the principal expert:

E1	1	1	1	5	5	1	1	3	5	5	4	1	1	1	5	1	1	
E2	5	4	3	1	1	5	5	1	1	1	5	5	5	5	1	5	1	5

The sum of the differences between these two ratings is  $4 + 3 + 2 + 4 + 4 + 4 + 4 + 2 + 4 + 4 + 1 + 4 + 4 + 4 + 0 + 0 + 0 + 4 = 52$ . Repeating this procedure for all the elements, E1-E10 (Table 8.1) the results in Table 8.3 were derived.

**Table 8.3:** Comparison of the elements (point-sources of groundwater pollution) - measurement of the differences between the elements ( $d_{ij}$ )

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
E1	-	52	31	30	31	41	35	38	26	34
E2		-	21	46	43	20	43	28	44	34
E3			-	29	28	29	32	29	33	27
E4				-	13	30	11	32	26	28
E5					-	29	12	31	33	29
E6						-	29	26	34	32
E7							-	33	33	31
E8								-	16	16
E9									-	18
E10										-

The next step is to calculate a measure of similarity between the elements; using the following:

$$\text{Measure of similarity (\%)} = \frac{-100 \times \text{difference between two elements } i \text{ and } j (d_{ij})}{\text{largest difference between constructs} \times \text{number of constructs}} + 100$$

$$\text{Measure of similarity (\%)} = \frac{-100 d_{ij}}{4 \times 18} + 100$$

For example, the measure of similarity between E1 and E2 =  $\frac{-100 \times 52}{4 \times 18} + 100$   
 = 28 %

The maximum value of  $d_{ij}$  is 72 as the largest possible difference between two constructs is four (i.e. 5-1) and there are eighteen constructs for each element. Two elements are considered similar if their measure of similarity is above 50% and dissimilar if below 50%. Table 8.4 shows similarity measurements for the ten elements (point-sources). Elements that are clustered together show the highest levels of similarity.

**Table 8.4:** Measurement of similarity (%) when comparing elements

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
E1	-	28	57	58	57	43	51	47	64	53
E2		-	71	36	40	72	40	61	39	53
E3			-	60	61	60	56	60	54	63
E4				-	82	58	85	56	64	61
E5					-	60	83	57	54	60
E6						-	60	64	53	56
E7							-	54	54	57
E8								-	78	78
E9									-	75
E10										-

From Table 8.4, the highest level of similarity is 85% between E4 and E7. The next highest level is between E7 and E5 at 83%, then E4 and E5 at 82%. Elements E4, E7 and E5 are clustered together. The principal expert thinks of these sites as similar, based on the constructs elicited (Table 8.2). Elements can be clustered together as follows:

**E4, E5 and E7 (82 to 85% similarity)**

Landfill site in opencast coal pit

Redevelopment of steelworks in the Black Country, West Midlands

PFA disposal into a gravel pit near the River Trent, East Midlands

**E8, E9 and E10 (75 to 78% similarity)**

Soakaway system from a housing estate

Effluent discharge to soakaway from an animal renderers on Chalk geology

Sewage sludge spreading in an area of Chalk geology

**E2, E3 and E6 (71 to 72% similarity)**

Domestic central heating tank failure

Road accident involving tanker spillage - chemicals

Leakage from a petrol station in Solihull, West Midlands

E1, a major chemical factory on the Sherwood Sandstone is not clustered with any other elements but is least like a domestic central heating tank (E2, 28% similarity).

When the principal expert ranked elements according to their overall risk to groundwater (on an individual basis) the results shown in Table 8.5 were obtained.

**Table 8.5:** The ranking of elements (point-sources of groundwater pollution) on the basis of risk to groundwater alone

Ranking	Element	
1	E1	Major chemical factory on the Sherwood Sandstone
2	E9	Effluent discharge to soakaway from an animal renderers on chalk geology
3	E3	Road accident involving tanker spillage - chemicals
3	E4	Landfill site in opencast coal pit
3	E8	Soakaway system from housing estate
3	E10	Sewage sludge spreading in an area of chalk geology
4	E5	Redevelopment of steelworks in the Black Country, West Midlands
4	E7	PFA disposal into gravel pit - R Trent, East Midlands
5	E6	Leakage from petrol station in Solihull, West Midlands
5	E2	Domestic central heating tank failure

This ranking represents what the principal expert feels personally about risks to groundwater. A major chemical works on the Sherwood Sandstone aquifer represents the highest risk to groundwater and is not like any of the other point-sources elicited. These results show that the principal expert personally feels that a leakage from a petrol-filling station presents a low individual risk to groundwater compared to a chemical factory. A domestic heating tank failure



was given the same individual rating score of 5 as the petrol-filling station but the road tanker spillage which was clustered with these other two point-sources, was given an individual rating of 3. So although a central heating tank failure, a leakage from a petrol-filling station and a road tanker accident are considered similar, in terms of risk to groundwater alone, the road tanker accident is considered to be a higher risk by the principal expert.

These results although highly personal do serve to support what might be considered the 'common-sense' answer that a chemical factory on the Sherwood Sandstone aquifer is 'obviously' more important in terms of risk to groundwater than a petrol-filling station. As a source term, the chemical factory presents a greater risk due, for example, to the volumes and types of potential contaminants that may be stored there. These results highlight petrol-filling stations as low risk to groundwater as individual sites but does not take account of any 'cumulative effect' of the large number of sites nationally. This is the way the principal expert perceives the situation, carrying out a similar exercise with someone else may not result in the same outcome: for example, someone charged with writing a national regulatory policy related to petrol-filling stations compared with someone charged with regulating individual stations.

The technique of repertory grid analysis reinforced what may have been felt by the principal expert before carrying out the sorting process, although it must be noted that it was a time-consuming and relatively complicated technique to use for such an output.

### **8.2.2 Interviews**

A series of interviews were carried out with the principal expert. The first interview was used to get an understanding of the problem area, what kind of system would be suitable and who might use it. The results of this were presented in section 8.1 as responses to the set of questions posed, as to whether a knowledge system approach would be suitable, appropriate, justified etc. (Table 6.1). A set of topic areas were identified before interviewing began (listed in section 7.2.2) which became general discussion 'themes' throughout the interview sessions with the principal expert.

During the second interview, the principal expert was presented with a hypothetical case of a 20,000 gallon underground diesel tank catastrophically rupturing and losing all its contents, this being reported by telephone, by the tank owner. The expert was asked to consider the problem and describe what they would do to deal with it. The objective of this interview was to gain an indication of:

- the types of information required to deal with the problem
- sources of such information
- an approximate order that these pieces of information were required

- how information was built up

It was clear during the interviews that the principal expert was using a Source-Pathway-Target model (discussed in Chapter 2, section 2.1.5) to think about the problem and how to deal with it. The expert evidently considered source terms and data first, followed by target issues then pathway issues. The reason given for considering targets before pathways (i.e. STP rather than SPT) was that the target term was often easier to characterise than the pathway term. In addition, the type of target (e.g. drinking water abstraction) dictated how the situation would be dealt with, in terms of resources for example. Information requirements etc. as identified are described below:

### *Source*

- What was the volume of fuel released ? Some kind of evidence supporting the volume size was usually required by the principal expert. In their experience when a site operator contacts the regulatory authority and states that a large volume has been lost, this is not always the case, mistakes can be made due to poor record keeping for example. Overestimating the size of the leak/spill can result in an 'over-response' to the incident. Conversely release size can be underestimated by the site operator for the same reasons that result in overestimation. In cases where there is doubt a 'worse-case scenario' is usually assumed by the regulator. For example, in the case of a leaking underground tank the total volume of the tank (or the compartment in use) is used as an assumed release volume.
- What type of contaminant has been released ? In the case of an underground fuel tank this is relatively easily answered as usually petroleum or diesel. A diesel release was perceived by the principal expert to present a higher risk to groundwater than one of petroleum (the properties of diesel and petroleum were discussed in Chapter 3, section 3.3 and this point is discussed further in Chapter 9, as part of system verification).
- What is the timescale of the release ? Has the site operator just noticed that their tanks have been leaking and this may of been going on for a long time, or has a tanker delivered a load which has 'disappeared' ?
- What is the volumetric loading of the spill/leak ? Again in the case of an underground fuel tank this will mean that the release is concentrated over a relatively small area with a large amount of fuel being released into a small amount of soil. This situation was considered to be worse in terms of risk to groundwater than if a leak/spill was released over a large area due to any possible attenuation properties of the soil being quickly 'overloaded' when a spill/leak was concentrated on a small area.

- What are the containment facilities at the site ? This is the most likely area for lack of information on the part of a regulator. Petrol-filling stations, although common, are not regularly monitored by Environment Agency staff (they are licensed but are regulated by a Petroleum officer, usually someone from the Fire Brigade). An Agency officer may not be familiar with the structure and lay-out of a typical retail site and any variations due to who is operating the site. Site plans are often out-of-date and the site manager may not know exactly where tanks and associated pipelines are located. There is no tank registration programme in the UK akin to that operated by the USEPA to ensure that tank construction information etc. is available to regulatory personnel. The information can be obtained but this often takes some time. If it is a new site or has been redeveloped recently (requiring planning permission) there will be more information available as the Agency is a statutory consultee for such planning applications.
- What is the access to the site like for site investigations ? This can be a consideration if the site owner is not co-operative.

### *Target*

- What is the groundwater vulnerability in the area of the incident ? Is the site over a 'major' (i.e. strategically important for water supply) aquifer for example. Groundwater vulnerability maps were used at this stage to provide a 'quick guide'.
- What is the current (or possible future) groundwater use ? Is it used for drinking water, agricultural use such as crop irrigation or industrial use such as cooling water. This factor was a major influence on how the problem was dealt with by the principal expert. If groundwater was used as drinking water, any incident would be treated more urgently although the same decision-making procedure would be applied for other uses but on a longer timescale. Groundwater itself was seen as the target of concern, although it was recognised that other targets such as humans were being protected in the case of drinking water.
- Are there any surface water bodies (e.g. lakes, ponds, streams, rivers etc.) nearby ? As a target, surface water bodies are seen as relatively important and worthy of protection but are sometimes only considered due to the fact that groundwater can be contaminated by surface water. This is reflective of the regulatory culture of the Environment Agency in terms of the development of policy priorities.
- What are the locations of the nearest groundwater boreholes ? Details of all licensed abstractions are kept on a register available to Agency staff (and the public). This

register gives a grid reference for each borehole. The closer a borehole to a site/incident, the greater the concern.

### *Pathway*

- What is the groundwater vulnerability in the area of the site or incident ? This information is used under the target and pathway elements of the decision process. In terms of pathway, vulnerability has been calculated using a variety of factors such as the nature of the strata, presence of drift etc. and is inherently risk-based.
- What is the permeability of the underlying aquifer ? This is not required in any great detail but if the aquifer is known to be highly permeable, which is much more likely if it has been designated a major aquifer, then concern is heightened.
- What is the groundwater flow rate ? Again an exact number is not required but a high flow could mean a high dilution rate or possible widespread contaminant movement.
- What is the depth of the unsaturated zone ? This is also linked to groundwater vulnerability and generally the greater the depth of the unsaturated zone the better, as there is more chance of any pollutants being attenuated as they pass through the soil matrix. The length of time available to deal with the problem may be increased if the spill or leak has to move through a greater distance to reach the saturated zone and groundwater.

Not surprisingly the principal expert relies heavily on their own knowledge and experience when dealing with a problem such as that described above. That knowledge has been built up over many years and comprises a 'database' of previous cases (with resulting outcomes) and a related store of heuristic knowledge (rules of thumb) which forms a highly personalised decision-making procedure (Chapter 5, section 5.1.2). However, importantly, the principal expert also uses external sources of information such as maps, site files and colleagues to supplement their decision-making process.

The results of this session and subsequent interviews are perhaps best represented by a series of flow-charts and accompanying discussion. Such flow-charts have been used to form the basis of a conceptual model of the problem area (or paper model) from which the computer-based system has been developed from. These are shown and discussed in Chapter 9. Information obtained from other acquisition techniques has also been used to develop the conceptual model but individual results are included in the remainder of this Chapter. The technique of 'protocol analysis' was used to build on the results obtained from the interview sessions, to generate a

plan of how the principal expert goes through their decision-making process: i.e. the 'order' in which information is collected and used.

### 8.2.3 Protocol Analysis

The technique used was 'off-the-job' protocol analysis where a selection of case studies were assessed by the principal expert; a leak from a petrol-filling station, leachate contamination from a landfill and a solvent leak from a factory site.

The main aim of using this technique was to focus on the 'chronology' of events, i.e. in what order the expert assesses the problem. The amount of time needed for each case study was significantly under-estimated and only two out of the three cases were studied in any detail by the expert. In addition, the principal expert was able to identify all the case studies presented to them, therefore an element of recall of actual events was introduced to the protocol which was not intended. However, despite the change in scope, useful insights into how the expert goes about assessing a problem were obtained.

The case study looked at in greatest detail was the factory site. This site was under investigation due to a spill of tetrachloroethene and tetrachloroethylene. The 'order of events' that the expert would undertake when assessing such a problem is shown in Table 8.6.

The principal expert also studied the petrol-filling station case and indicated that they would follow a very similar process and had similar information requirements to that reported for the factory site (Table 8.6). Differences occurred at the start of the process when considering the source of the pollution. More information was known about the volume of the leak and exactly where it had come from i.e. the leaking tank was identifiable. Even though the volume of the release was provided by the site owner in this case, the expert would normally assume the worst-case scenario of the whole tank contents being lost, therefore the amount of fuel the tank contained when full is an important piece of information to obtain. Another difference was the issue of who owned and operated the site. The expert was more likely to trust information supplied by a larger well-known operator than a single owner/operator. This also extended to what action the site operator took to resolve the situation, the actions of a larger company being trusted more than those of a single/owner operator.

The results of these protocols are particularly useful in determining 'what happens next' in carrying out a site assessment. That information has been used to generate a range of flowcharts describing the decision-making process and forming the basis of a conceptual model of the problem area. This process is discussed more fully in Chapter 9.

Table 8.6 : Off-the-job protocol taken from the principal expert when assessing the risk to groundwater from a textile factory

Question	Action/Outcome	Information obtained from
Assess site for potential/actual groundwater pollution	Apply the source-pathway-target model to achieve a risk-based assessment of the site	Personal experience
What is the source?	Study the site plan and maps, investigate industrial units nearby to check that the factory is the primary source	Site plans, maps and site visits
What is the hazard?	Spill was of tetrachloroethene and tetrachloroethylene (PCE) but a soakaway for PCE contaminated water was found at the site. The drinking water concentration for PCE is 10µg/l and is a similar level for surface waters, it is a highly hazardous pollutant. If the pollutant was unknown to the expert, toxicological information would be obtained	Personal experience, reference texts e.g., toxicological data sheets, colleagues
Where has pollutant been released from, an exact location	Detailed site visit	Personal site observations and consultation with factory staff
What potential targets may be impacted?	Potential targets searched for, the actual pathway element was assessed last as it was seen as the most 'difficult bit'. Targets searched for first were people using the groundwater as drinking water via private or public boreholes	Personal experience, abstraction licence records (for >10m <sup>3</sup> /day yields) Environmental health officers for single dwellings with private boreholes
Other potential targets?	Search for other abstraction boreholes for agricultural or industrial use. Order of target 'importance' - drinking water uses (public & private) ⇒ hospital use ⇒ food processing use ⇒ agricultural use ⇒ non-consumable industrial use e.g., steel quenching None of the above targets found - check for surface water bodies within 200m	Personal experience, abstraction licence records, maps
Potential pathway for pollutant to affect targets?	Pathway assessment carried out after target assessment. Check aquifer type, depth of unsaturated zone, potential transport time of pollutant, potential for attenuation in soil	Personal experience, consult with colleagues, maps
Is site still an immediate problem?	Collate data on source, pathway and target - is the release still an immediate problem	Personal experience, consult with colleagues
If no emergency action is required	Carry out a semi-quantitative risk assessment and generate a 'worst-case scenario' e.g., nearby borehole is polluted to such a level alternative supplies must be found. Need to show that: (i) worst-case scenario not likely to happen (ii) source of pollution is removed	Personal experience, consult with colleagues, desk study, liaison with polluter
Is worst-case likely?	Carry out a site investigation to learn more about hydrogeology at the site	Personal experience, consult with colleagues
Remediate or not?	Investigate soakaway, check that no targets will be impacted in the future based on possible remediation strategies. Look at site and surrounding areas	Personal experience, consult with colleagues, liaison with polluter
Overall aim?	Primary objective of any assessment is to deal with any immediate problems and those that require an emergency response first before going on to investigate the site further	Personal experience

## 8.2.4 Concept Sorting

During the interview sessions with the principal expert it became apparent that a large number of 'keywords' or concept words were used by the expert when describing their decision-making process, for example when assessing an underground tank leak at a petrol-filling station. These concepts could be sorted into categories such as 'source terms', 'pathway terms' and 'target terms' represented by the Source-Pathway-Target model of risk-based site assessment.

Using the technique of 'concept sorting' the principal expert was able to sort a set of concept words that they had devised into a range of different 'sort categories' also devised by them. These sort categories are shown in Table 8.7. These concept words and sort categories were subsequently used with other participants such as other Environment Agency staff, environmental managers in industry and academics, who also carried out the sorting process.

**Table 8.7:** Concept sort categories

Sort No.	Sort Categories
1	Source; pathway; target; irrelevant
2	High; medium; low risk to groundwater; irrelevant
3*	Critical; very important; important in terms of risk; irrelevant
4	Sufficient information to do something yourself; ask for more information; pass it on to a specialist; irrelevant
5	Do something immediately; longer term action; little/no action; irrelevant

\* This is a sub-sort of 2

Table 8.8 shows some examples of the concept words elicited from the principal expert and used in all the sorts conducted with the principal expert and other participants. A full list of the 90 concept words is shown in Appendix B.2.

**Table 8.8:** Example concept words elicited from the principal expert and sorted into source, pathway, target and irrelevant terms

Sort Category	Card No.	Concept
<i>Source</i>	8	Volume of spill is < 10,000 litres
	61	Mineral oil spill
	76	Petrol spill on soil surface
<i>Pathway</i>	10	Groundwater vulnerability - minor aquifer
	28	Groundwater flow is high
	47	Mainly clay strata
	58	Strata are fissured
<i>Target</i>	20	Target within 500 m
	37	Drinking water abstraction < 1km away
	52	Abstraction for agricultural/industrial use nearby
<i>Irrelevant</i>	26	Specialist groundwater staff available for communication
	90	Intrinsic bioremediation

Each sort was performed by between seven and twelve people. In each case, the results were compared back to the principal expert as a measure of agreement with the expert. Figure 8.1

illustrates how the level of agreement with the expert can vary with the number of concepts or on an individual basis (how well a person agrees with the expert across all concepts). For example, a level of 90% of concepts might give 20% or less agreement with the expert in the case of poor agreement.

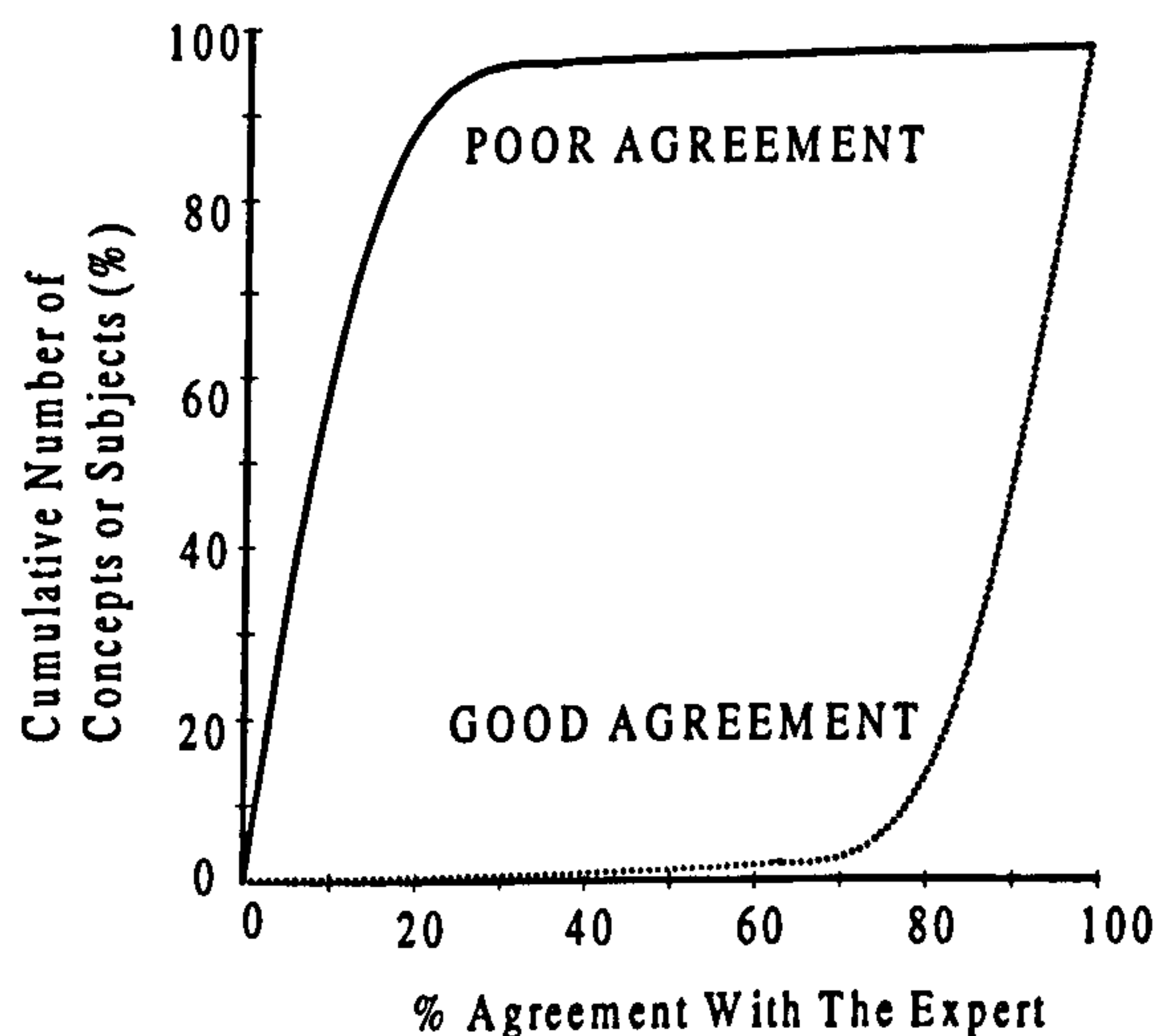


Figure 8.1: Illustration of agreement with the expert across all concepts.

Figure 8.2 shows the level of agreement or disagreement that was obtained across all sorts when comparing back to the principal expert. Sort 1, when people were asked to sort the concept words into source, pathway and target terms, gave the highest agreement with the expert. For Sort 1, less than 30% of the concepts gave an agreement level of less than 50% with the expert.

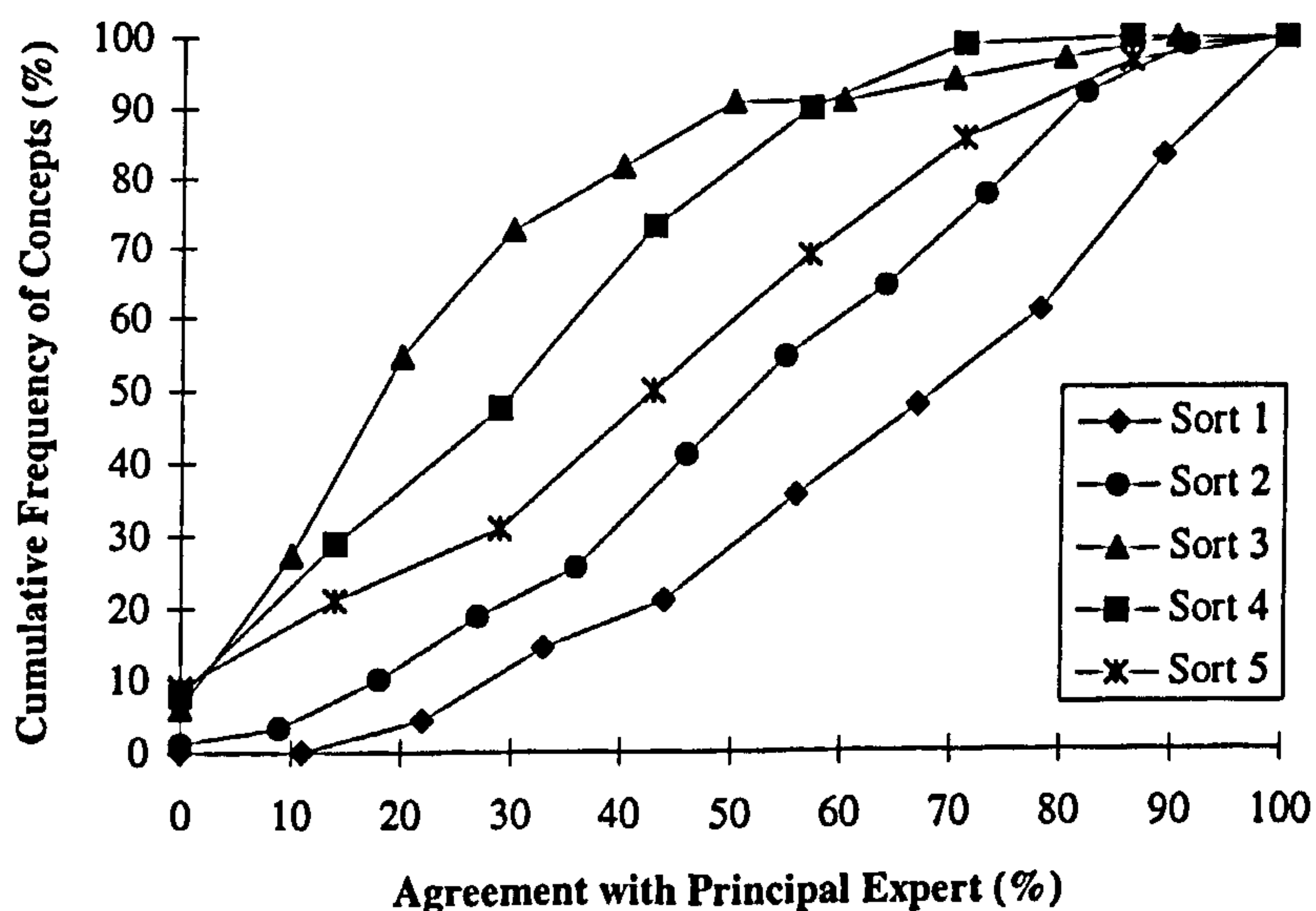


Figure 8.2: Measure of agreement with the principal expert across all concepts and all sorts  
With Sort 2, participants were asked to sort concepts on the basis of high, medium or low risk to groundwater and this gave the next highest level of agreement with the expert, approximately



45% of the concepts gave an agreement level of 50% or less with the expert. Sort 3 was actually a sub-sort of 2, as those concepts put into the 'high risk' category during Sort 2 were then re-sorted for Sort 3 to provide a more detailed look at those concepts considered to be most important in terms of risk to groundwater. Not surprisingly as the concepts had to in effect be sorted twice, exact agreement was low, almost 90% of the concepts gave an agreement level of 50% or less with the expert. However, if the level of agreement for Sort 3 is limited to agreement on the actual concept word (i.e. those concept words chosen by the expert as 'high risk' and also chosen by the other participants as high risk but not necessarily put into the same sort category by them as chosen by the expert (critical, very important etc.)), the level of agreement is much higher with just over 30% of concepts at an agreement level of 50% or less with the expert.

With Sort 4, participants were asked to sort concepts on the basis of information requirements: i.e. whether they had enough information to proceed themselves, whether they need more information or whether they thought it needed passing to a specialist. Agreement with the expert on this basis should be low as the expert should feel they have enough information and can deal with the problem on more occasions than a 'non-expert' would be expected to. In order to become an expert in a field a certain level of knowledge and experience must be gained which can be used when making decisions, a non-expert would not be expected to perform at the same level. This was found to be the case with a relatively low agreement of 80% of concepts at an agreement level of 50% or less with the expert.

Sort 5 was in effect a second way of asking for the concepts to be sorted on the basis of risk to groundwater (Sort 2) but without using the term 'risk'. Participants sorted concepts according to 'response time': i.e. immediate action, longer term action etc. The level of agreement with the expert was lower than that for Sort 2. Approximately 60% of concepts fell into the 50% or less agreement category, which is approximately 10% higher than for sort 2. This is perhaps to be expected due to not using an 'emotive prompt' word like risk. However, it might also reflect different degrees of 'response responsibilities': i.e. some participants may not of been used to making decisions about response times as part of their duties.

Using the same data, agreement across participants as opposed to concepts, can also be presented for the five Sorts. These results are shown in Figure 8.3.

For Sort 1, approximately 20% of participants achieved 50% or less agreement with the expert. A similar pattern to that shown in Figure 8.2 is found, with Sorts 3 and 4 showing the lowest levels of agreement.

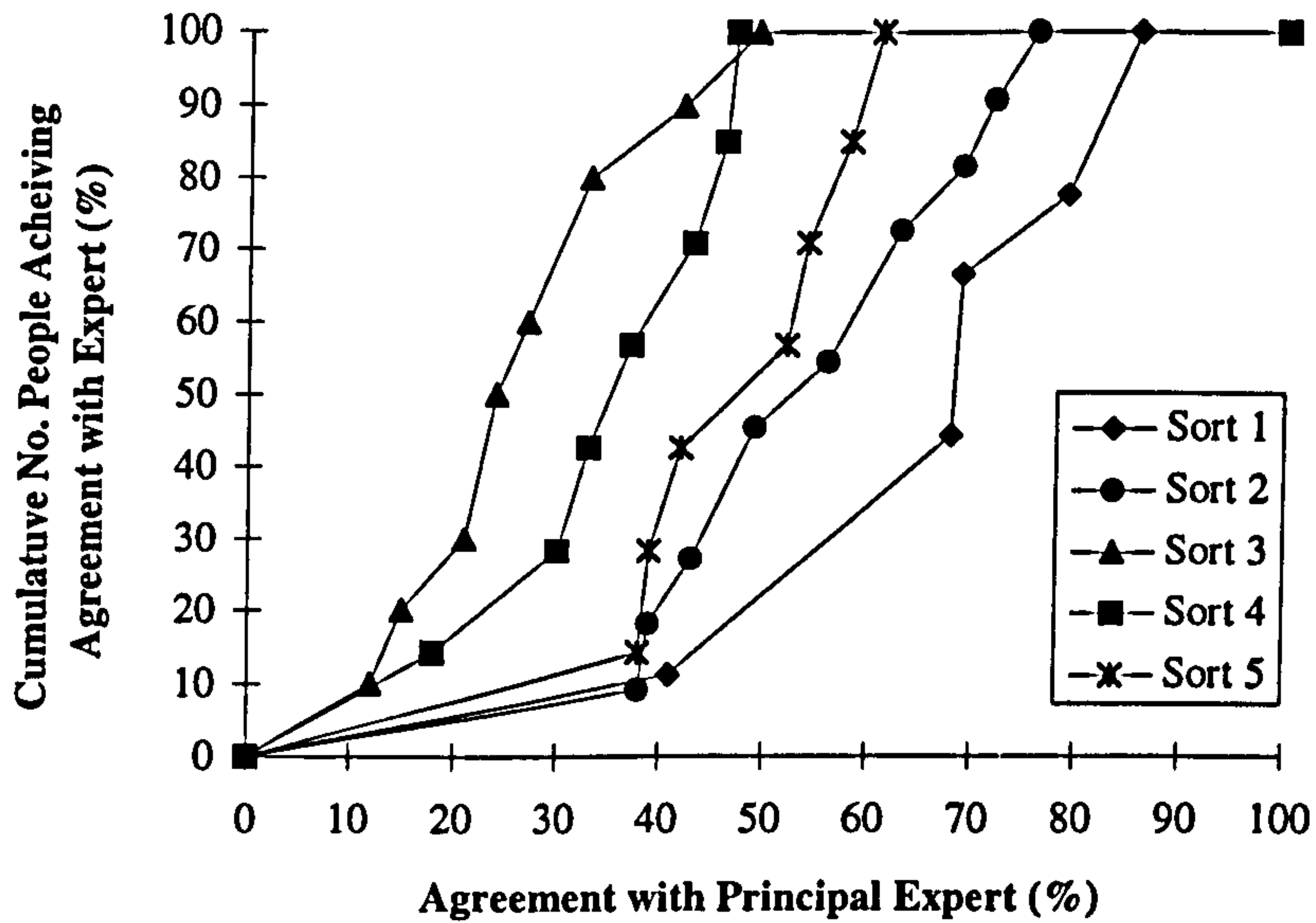


Figure 8.3: Measure of agreement with the principal expert across all participants for all five sorts

In order to investigate further the different levels of agreement with the principal expert across the various Sorts, concept words were split into five groups: those achieving 0-20% agreement, 21-40% agreement, 41-60% agreement, 61-80% agreement and 81-100% agreement. These results are shown in Figure 8.4 (a-e).

Sort 1 (Figure 8.4) where concepts were categorised into source, pathway, target and irrelevant terms, showed the highest levels of agreement with the expert, with no concepts in the 0-20% agreement category and approximately 39% of concepts in the 81-100% agreement category (compared to sort 4 for example, with approximately 30% in the 0-20% agreement category and 2% in the 81-100% category). It is also useful to identify exactly which type of concepts make up the percentage found in each agreement category and for Sort 1 this is shown in Figure 8.5.

Source and pathway concepts showed a similar distribution, perhaps implying that these type of concepts can be categorised more easily by participants in accordance with expert performance. Target concepts achieved an even higher level of agreement than pathway and source concepts. Discrepancies arose when categorising what is considered to be an irrelevant concept word. The level of agreement with the expert was much lower, mostly below 60%.

Sort 2 (Figure 8.4) where concepts were categorised into high, medium, low and irrelevant in terms of risk to groundwater, showed the next highest level of overall agreement with the expert. Only 10% of concepts fell into the 0-20% agreement category, with approximately 20% of concepts in both the 81-100% and 61-80% categories. The agreement category with the highest number of concepts was the 41-60% category. Investigating this further, Figure 8.6 shows how each sort category choice is distributed in terms of agreement with the expert. The high risk

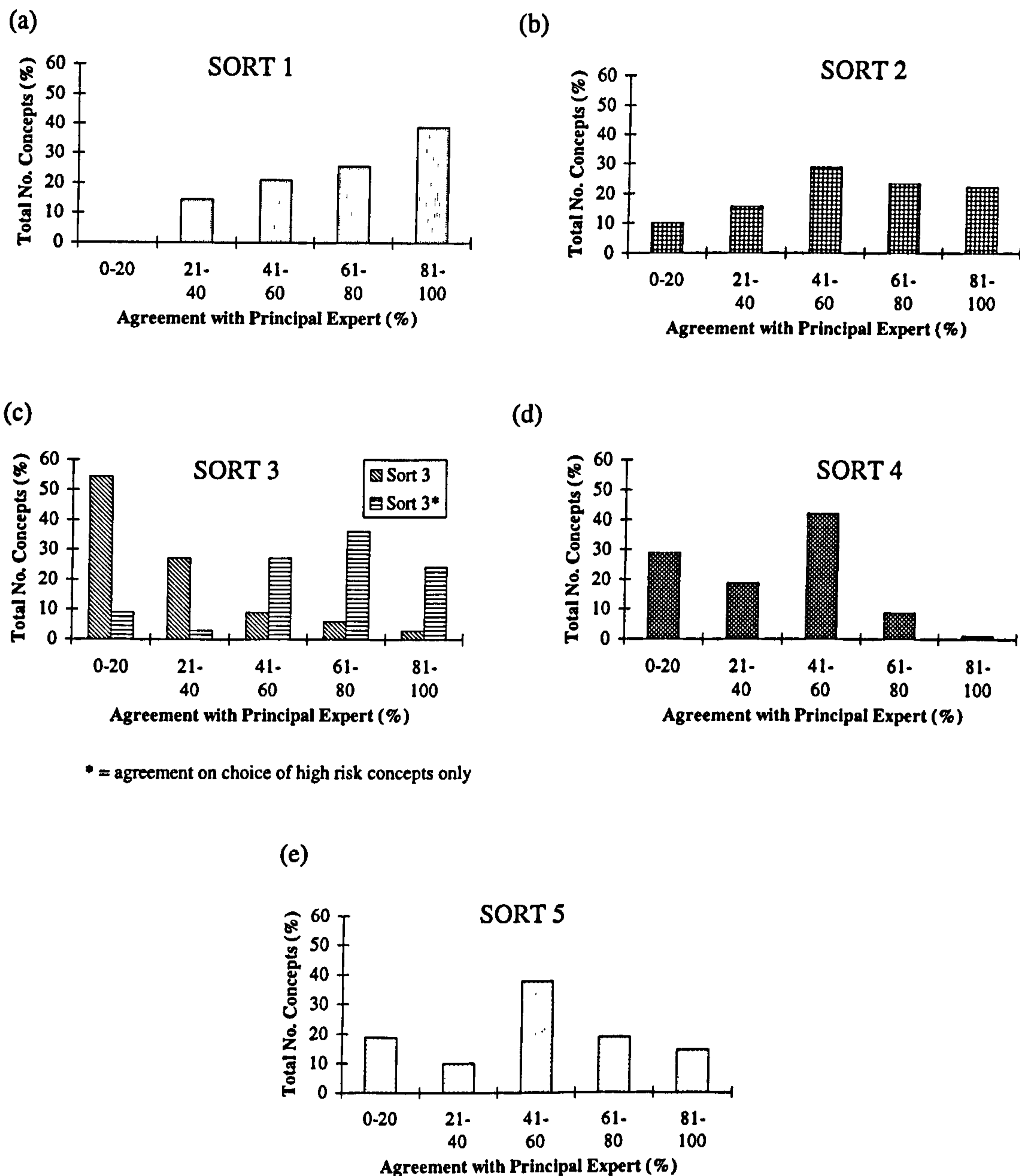


Figure 8.4: Distribution of levels of agreement with the principal expert across all concepts

category shows a higher level of agreement with approximately 50% of concepts in the 81-100% agreement category. This implies that high risk concepts are the easiest to identify and categorise as an expert would. This is also true to a lesser extent with irrelevant terms, the majority of concepts showing relatively high levels of agreement. This is a different pattern to that found in Sort 1, where there were relatively few concepts in the 61% and above agreements categories for irrelevant. Participants would appear to be less successful at sorting irrelevant concepts as the expert would in terms of source-pathway-target as opposed to categorising them in terms of risk to groundwater i.e. when sorting concepts in terms of risk to groundwater there was greater agreement with the expert over what was an irrelevant term.

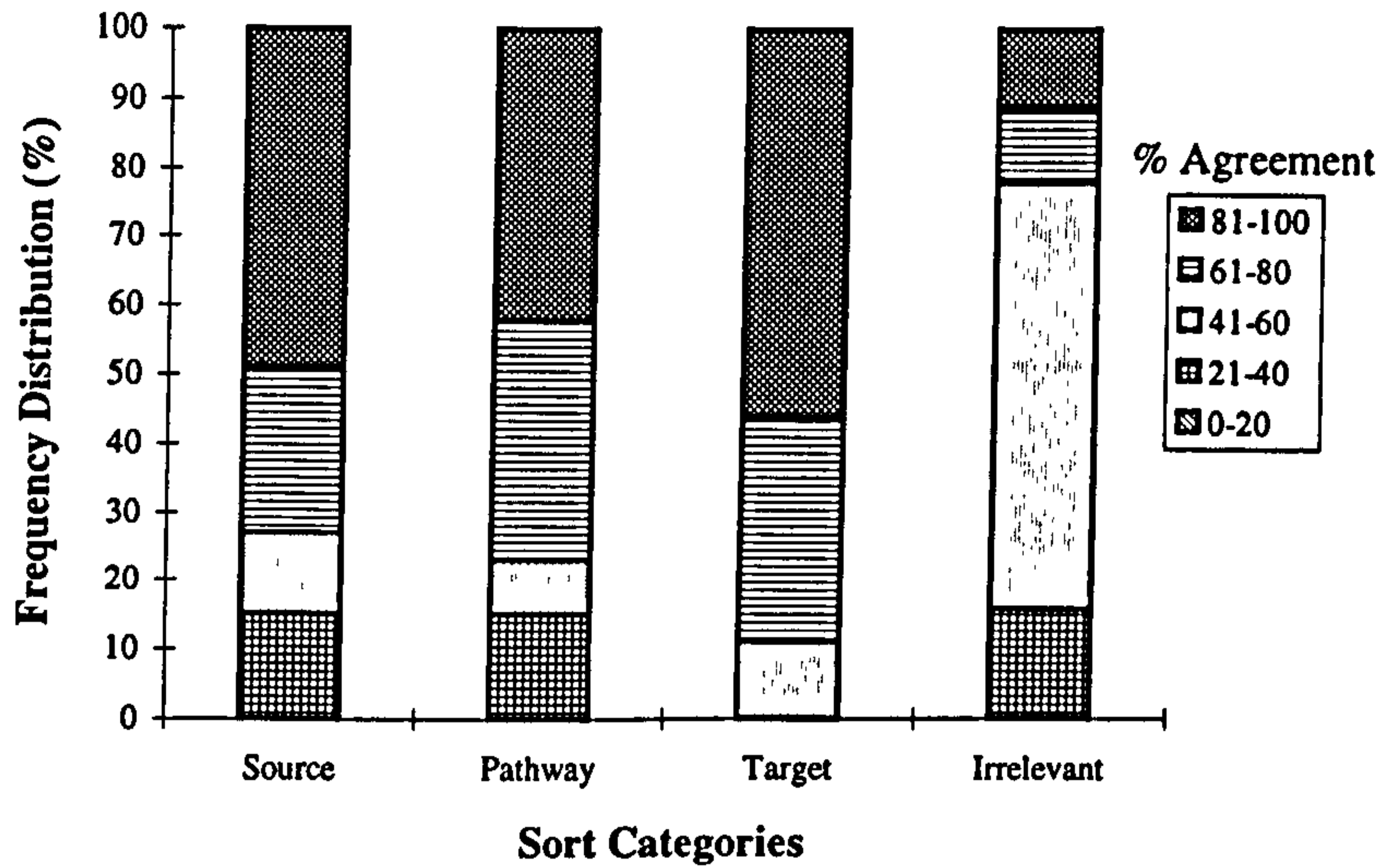


Figure 8.5: Distribution of concepts for each level of agreement (%) for Sort 1

The agreement levels for medium and low risk categories are also relatively low compared to the high risk category. This may be due to the way the words 'medium' and 'low' were interpreted by participants. 'High' and 'irrelevant' can perhaps be more easily defined as the 'maximum' and 'zero' options or extremes of the scale whereas the definition of 'low' and 'medium' is more subjective.

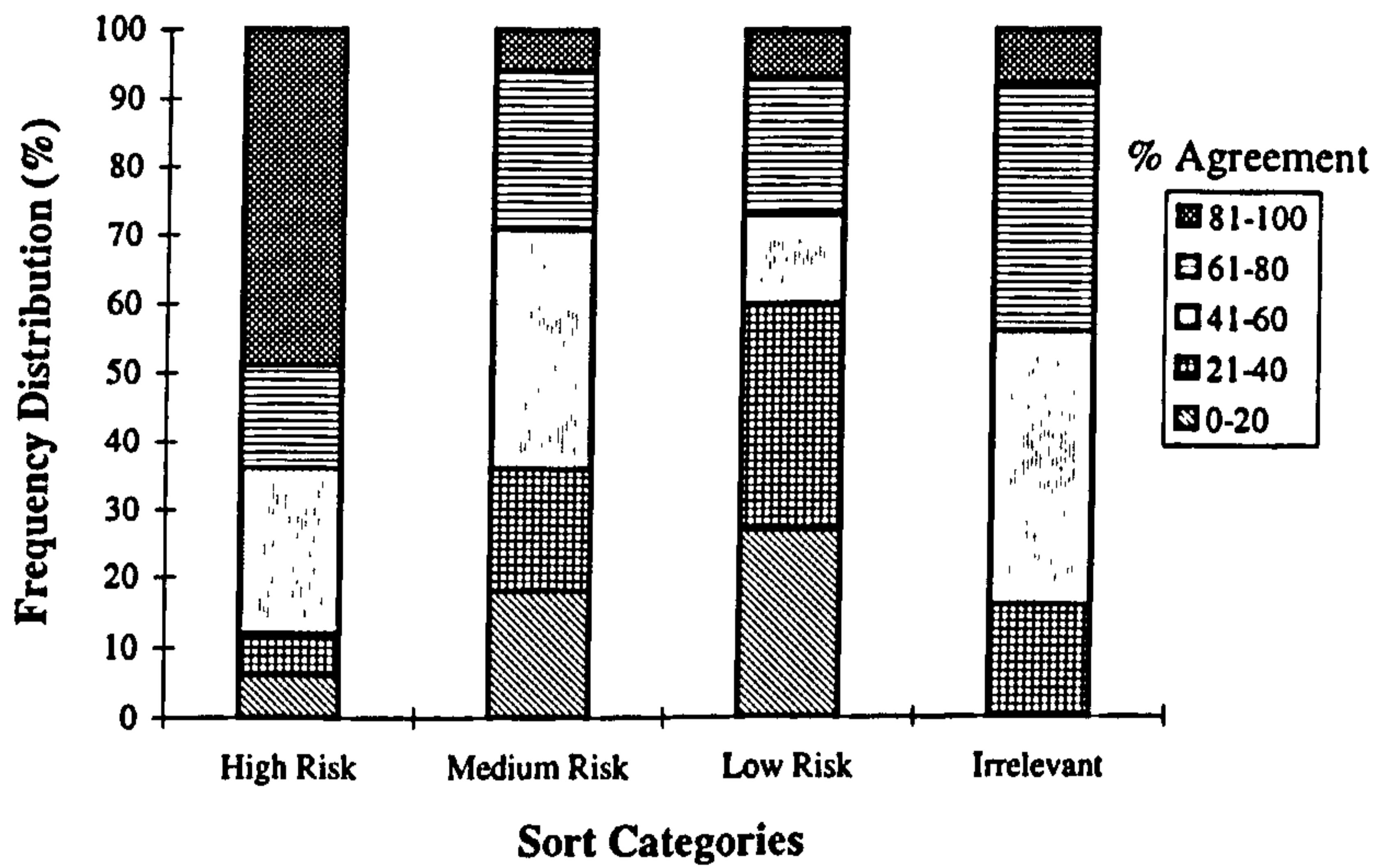


Figure 8.6: Distribution of concepts for each level of agreement (%) for Sort 2

Sort 3 (Figure 8.4) gave the lowest level of agreement with the expert (compared with the other Sorts), as it was a sub-sort of 2 and as concepts were effectively being sorted twice this was to be expected. Over 50% of concepts were in the 0-20% agreement category, with approximately another 25% in the 21-40% category.

If a comparison is made between agreement on the selection of specific concepts for the high risk category in Sort 2, we get the data shown in Sort 3\*. This shows a much higher level of agreement than Sort 3, which is possibly confused by the subtle differences in wording between 'critical', 'important' etc. This confirms that high risk concepts can be identified by the 'non-expert' in a similar fashion to the expert.

Figure 8.7 shows that there is a high level of disagreement about sorting concepts into those that are critical, important etc. in terms of risk to groundwater. There was very low agreement (all below 20%) in deciding which concepts were not quite so important but agreement increased when deciding which concepts were critical. This may imply that the non-experts tended to over-estimate the importance of concepts by not categorising them as not so important but were able to identify more concepts as critical in accordance with the expert.

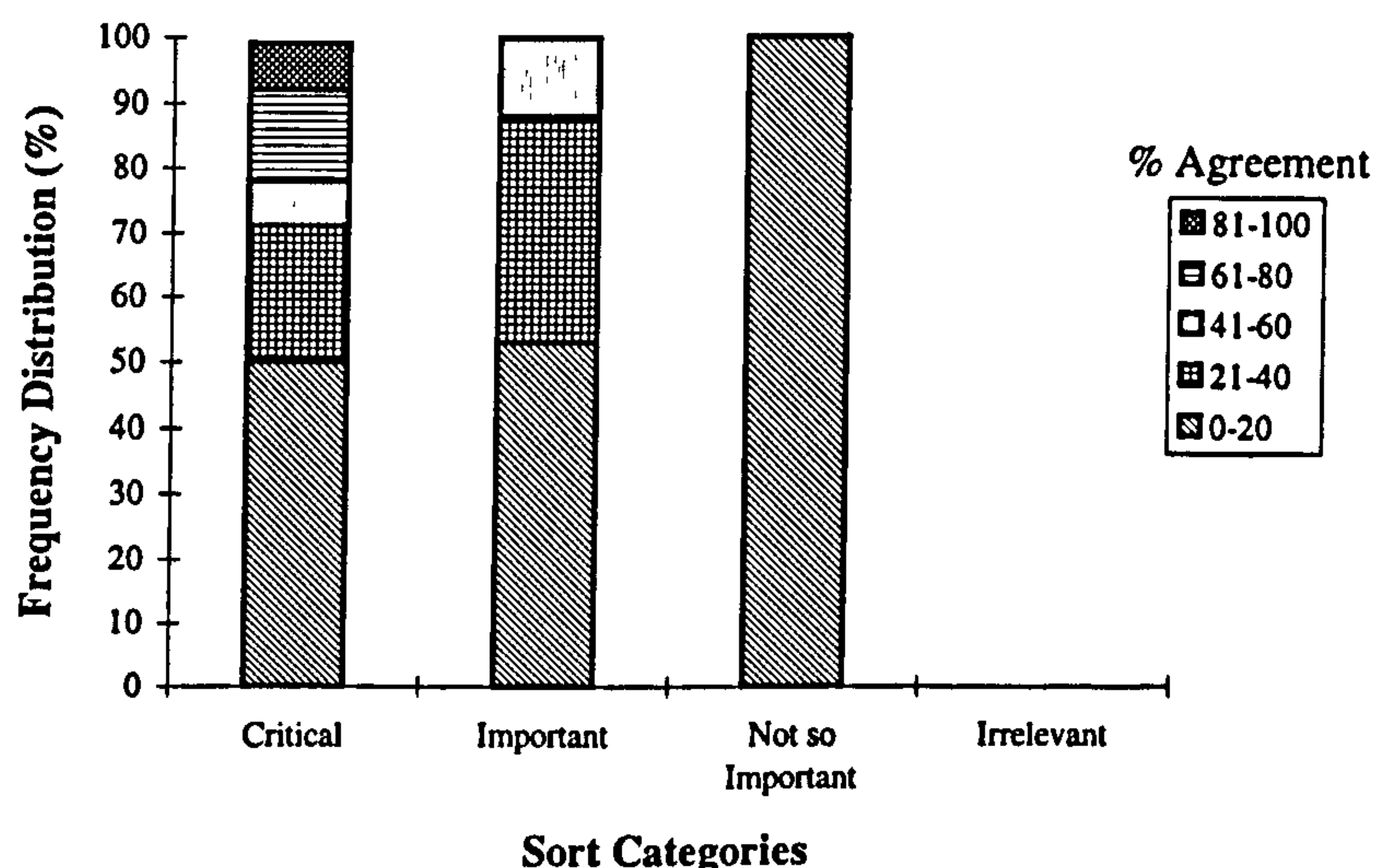


Figure 8.7: Distribution of concepts for each level of agreement (%) for Sort 3

For Sort 4, concepts were categorised in terms of 'information requirements'. In Figure 8.4, there is relatively low agreement with the expert, with approximately 90% of concepts falling in the 60% or less agreement categories. This would be expected for this type of sort as if there was a high level of agreement, participants would be performing at the expert level. Figure 8.8 shows that there are high levels of disagreement in deciding when there is sufficient information to deal with the problem and also when deciding if a concept is irrelevant in information terms. The highest levels of disagreement occur with the decision whether to pass something on to a specialist or not. Again, this is not surprising as the expert *is* a specialist to whom others pass problems on to. When the expert passes a problem to someone else it tends to be put to a specialist environmental consultant who will have more time to study the problem in detail.

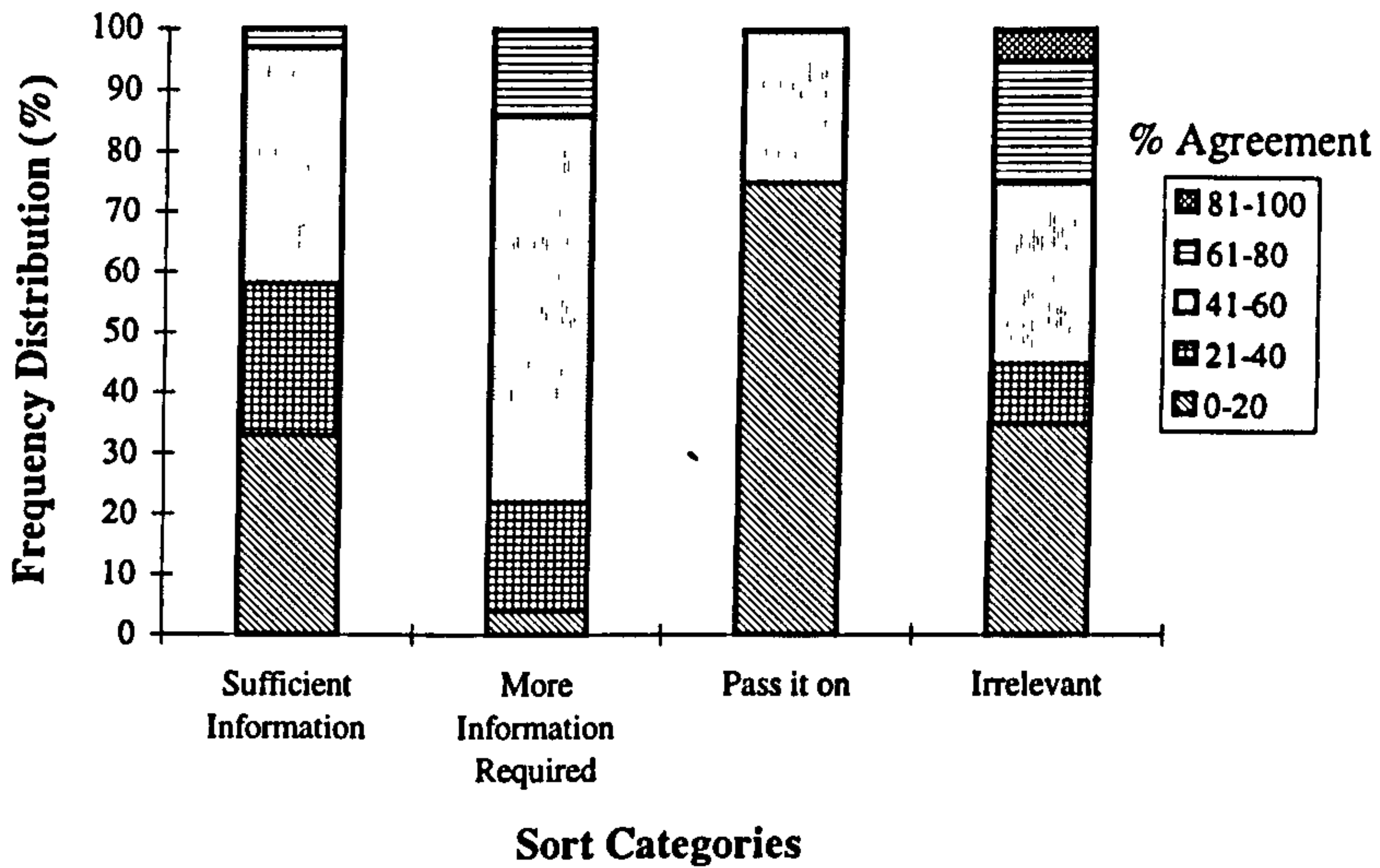


Figure 8.8: Distribution of concepts for each level of agreement (%) for Sort 4

Sort 5 (Figure 8.4) showed the third highest level of agreement (compared to the other sorts) with approximately 35% of concepts falling in the 61% and above agreement categories. The agreement category, 41-60% had the most concepts at nearly 40%. Figure 8.9 shows where the best agreements were. Deciding whether something required immediate action gave good agreement with the expert, approximately 45% of concepts showed an agreement level of greater than 61%. Agreement in deciding whether something required longer term action was lower, with only 30% of concepts in the greater than 61% agreement categories, with an increased number below 40% agreement. This pattern was also repeated for irrelevant terms. The greatest amount of disagreement arose over whether something required little or no action.

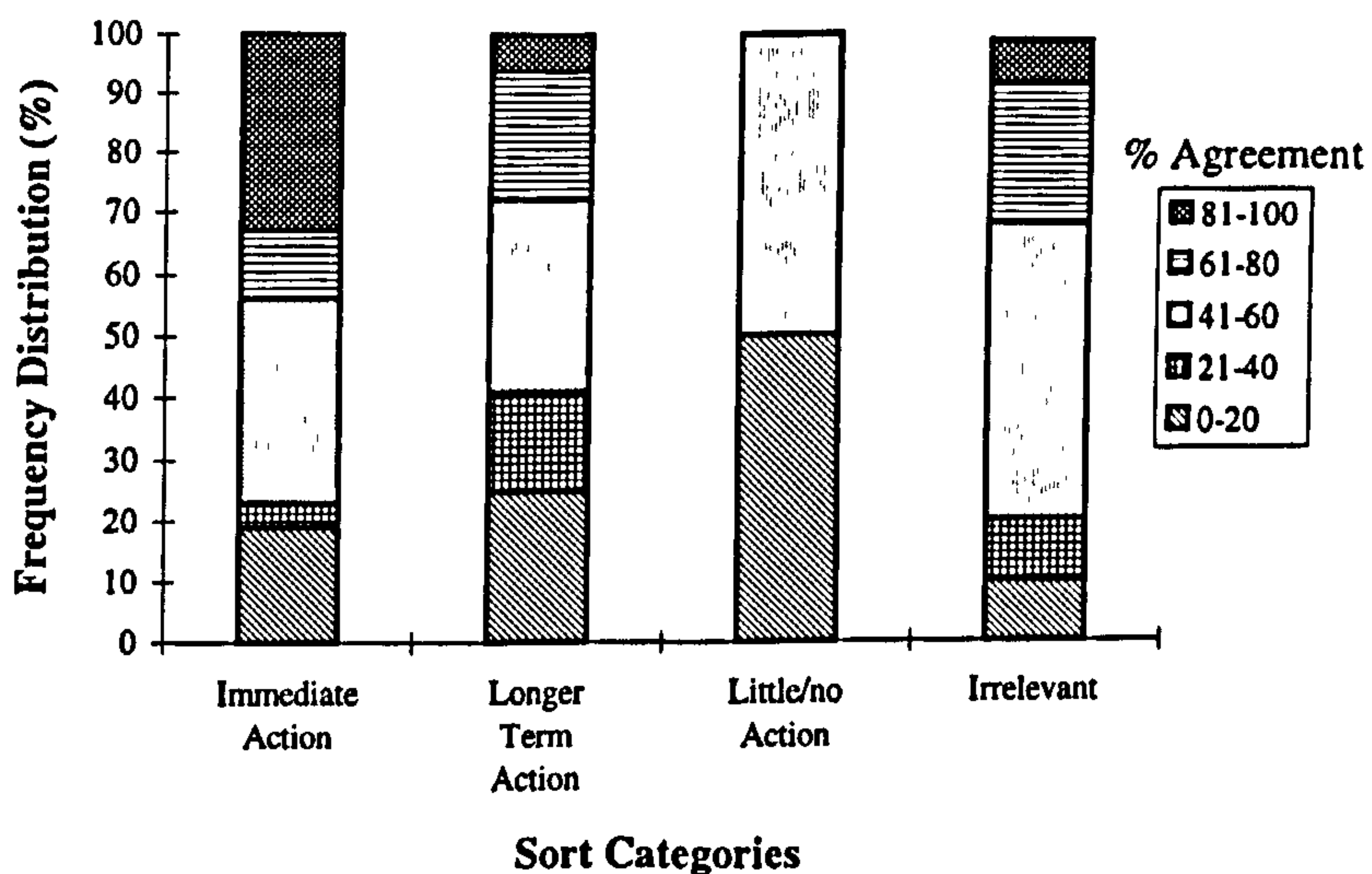


Figure 8.9: Distribution of concepts for each level of agreement (%) for Sort 5

As discussed earlier, Sort 5 was similar to Sort 2 although the words 'risk to groundwater' were replaced with 'response time', both were in effect describing similar situations, in that if a concept is high risk an immediate response is required. Comparing Figure 8.6 and 8.9 a similar pattern is observed. The only major difference being the 'low risk' category in comparison to 'little/no action'. Levels of agreement were higher for deciding if a concept was 'low risk', this may be because asking someone to sort concepts on the basis of 'risk' is more explicit than on the basis of response time.

As the sample sizes used with the concept sorting technique were relatively small (the technique can be used with small numbers, even a single participant) the data were analysed further to check that the results obtained were not random and that the principal expert does perform at a higher level. This was done by investigating the *scale* of the differences between the expert and other participants. For example, the difference between a concept being categorised by the expert as high and by other participants as a medium risk could be due to the way in which the words 'high' and 'medium' are interpreted, and the actual difference may not be large. However, the difference between high risk and irrelevant is not likely to be due to the way the words are interpreted and the difference should be genuine.

Investigation of these 'scales of difference' was carried out on Sorts 2, 4 and 5. Sort 1 was excluded as the terms, 'source', 'pathway' and 'target' are discrete, descriptive words: i.e. there cannot be a scale between a pathway term and a target term for example. Sort 3 was excluded as it was effectively a 'double sort' and not compatible in terms of scale with Sorts 2, 4 and 5.

An example of how the differences between the principal expert and other participants were calculated is shown below. The principal expert categorised the concept 'Permeability of aquifer is low' as 'low risk' (score 3) and requiring 'longer-term action' (score 2). Another participant, for example a waste regulator categorised this concept as 'medium risk' (2) and requiring 'longer-term' action (2). For these two sorts and this particular concept, a difference of 1 is obtained. by summing all the differences across sorts an arbitrary measure of agreement can be calculated.

For example:

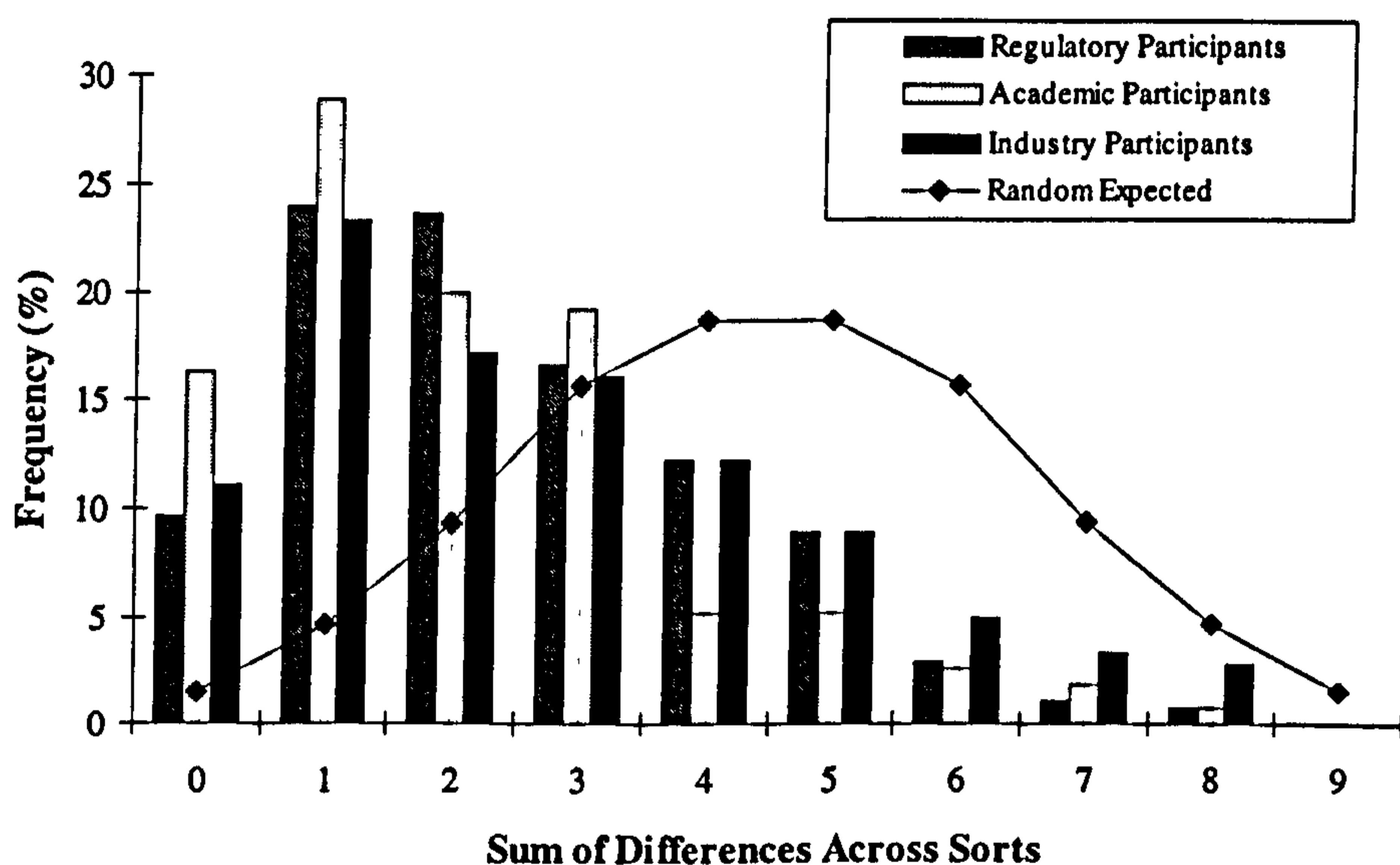
Concept: *Permeability of aquifer is low*

	Principal Expert	Score	Waste Regulator	Score	Difference
Sort 2	Low risk	3	Medium risk	2	1
Sort 5	Longer-term action	2	Longer-term action	2	0
					Total Difference = 1

This 'measure of agreement' was then used to illustrate that there are differences in performance of the principal expert and other participants. Sorting these concepts is not a random process

and an element of expertise is required. By calculating the difference between how the expert and how a participant sorts a concept and by summing these differences for each participant group (academics etc.), it is possible to show that there is a difference compared to that which would be expected if the sorting process had been a random one.

Figure 8.10 shows the overall results of each group of participants compared to the random distribution. The maximum difference per concept per sort is 3 (4-1) and therefore the maximum difference per concept across sorts 2, 4 and 5 is 9. For all three groups the sum of the differences is biased towards the lower end of the scale: i.e., 0, 1 and 2. A difference of 0 represents complete agreement on Sorts 2, 4 and 5, whilst a difference of 1 represents the sorting of a concept into a different category from the principal expert on one sort only.

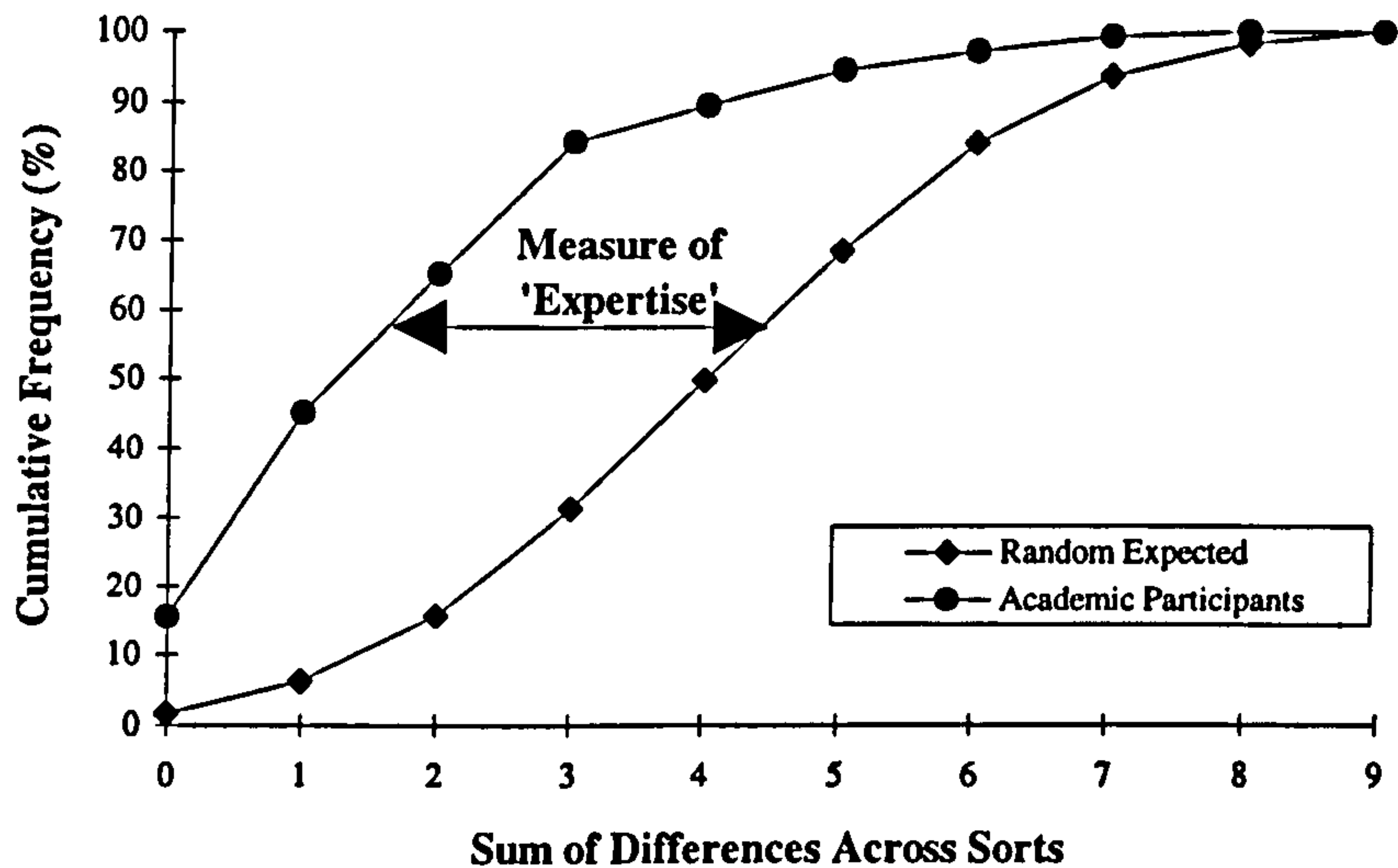


**Figure 8.10:** Distribution of the sum of the differences with the principal expert, for regulatory, academic and industry participants, for all sorts, compared to the expected distribution if the sorting process were random

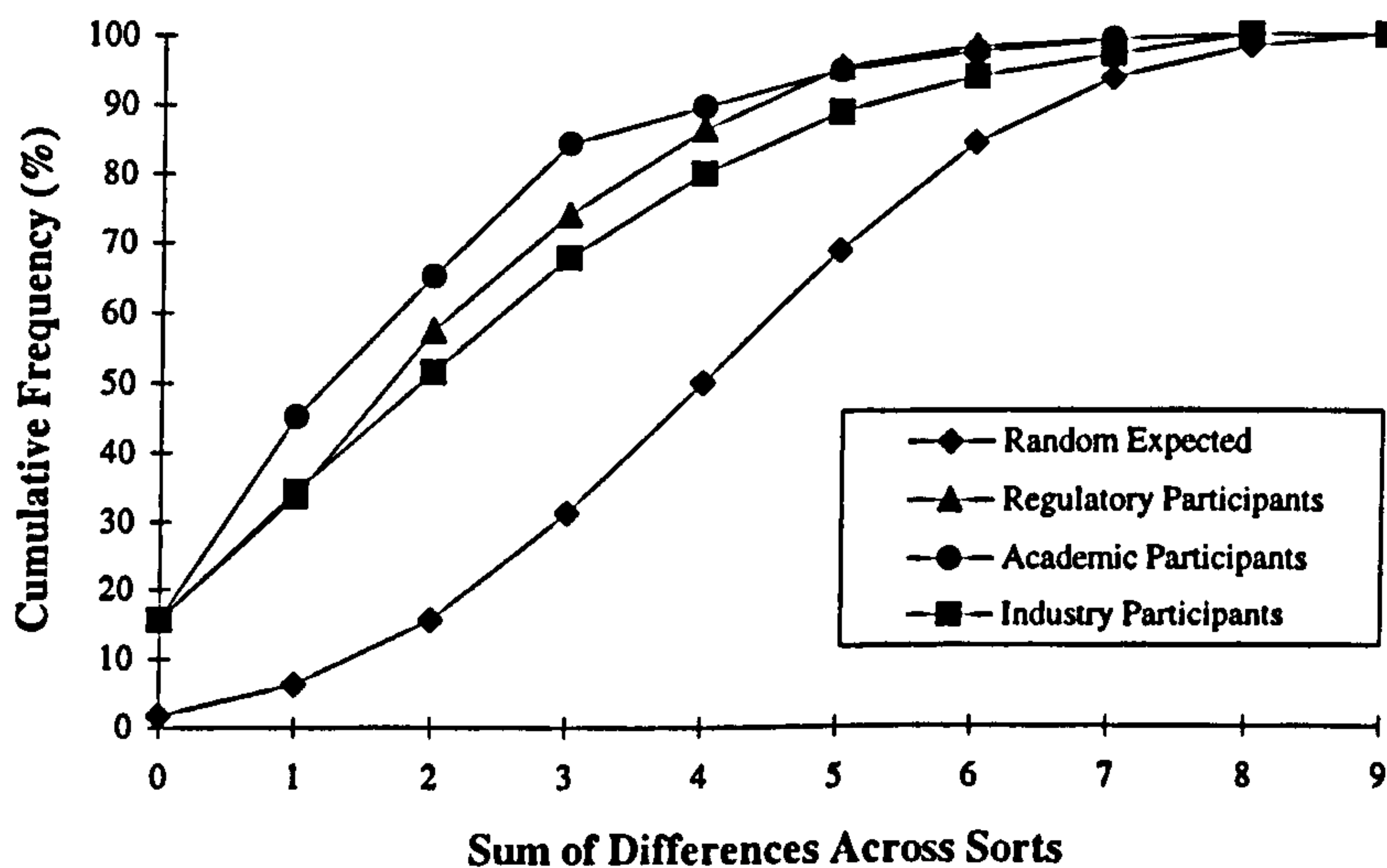
Figure 8.11 shows the cumulative distribution for the differences between the principal expert and the academic group of participants with the random expected distribution for comparison. For over 50% of concepts, agreement was high with differences of 2 or less across all sorts. This 'expert distribution' can then be compared to the distribution that would be expected if the sorting process had been a random one and the difference termed a 'measure of expertise'. This is purely an arbitrary measurement of expertise, but it is useful in showing that expert performance is different from a random sorting process.

Using a cumulative frequency distribution, the differences between each group of participants and a random distribution becomes clearer (Figure 8.12). The academic participants show greater agreement than the regulatory participants, who in turn show slightly greater agreement than the industry participants, all when compared back to the principal expert.





**Figure 8.11:** Illustration of a 'measure of expertise' where performance of the academic participants against the principal expert is compared to what would be expected if the sorting process were random



**Figure 8.12:** Cumulative distribution of the sum of the differences with the principal expert, across Sorts 2, 4 and 5, for regulatory, academic and industry participants, compared to the random distribution

In summary, participants were more successful at sorting concepts into source, pathway and target terms than sorting on the basis of risk to groundwater, whether they had sufficient information or length of response time. The greatest discrepancy arose with Sort 4, sorting on the basis of information requirements. This is to be expected as if agreement had been high, participants would have been performing at the same level as the principal expert on a task that essentially requires expert knowledge in order to be conducted effectively. All participants were, however, performing better than would be expected if the sorting process had been a random one (Figure 8.10). The academic participants showed the greatest levels of agreement with the principal expert across sorts 2, 4 and 5 and were used to describe a 'Measure of Expertise', the difference in performance from the random to the 'expert'.

Application of the information obtained from the concept sorting exercise is discussed further in Chapter 9 with the generation of the conceptual model. The final technique used as part of the knowledge acquisition phase of this research was a 'risk rating' exercise.

### 8.2.5 Risk Rating Exercise

This exercise was carried out by the principal expert, a regulator, an academic and two representatives from industry. Concept words were presented to the participants as a series of tables based on the source-pathway-target model. This was different to presentation during the original 'concept sorting' where the terms were presented randomly to each participant. Table 8.9 shows the tables used. Concept words obtained for use in the sorting process were included but a large range of other concept words were also added. Details of all the concepts used are shown in Appendix B.3.

**Table 8.9:** Structure of the categories that concept words were presented to participants

Table No.	Category Title
1	Source terms - not specific to petrol stations (product hazard)
2	Source terms specific to petrol stations (product hazard)
3	Source terms associated with the delivery of petroleum (delivery hazard)
4	Source terms associated with the storage and distribution of petroleum (storage & distribution hazard)
5	Source terms associated with dispensing of petroleum (dispensing hazard)
6	Overall site control measures at a petrol station (control procedures)
7	Pathway terms
8	Target terms

The terms were rated with reference to three different 'characteristics' (as described in Chapter 7, section 7.2.5):

- (i) Hazard rating
- (ii) Information requirements
- (iii) Response time

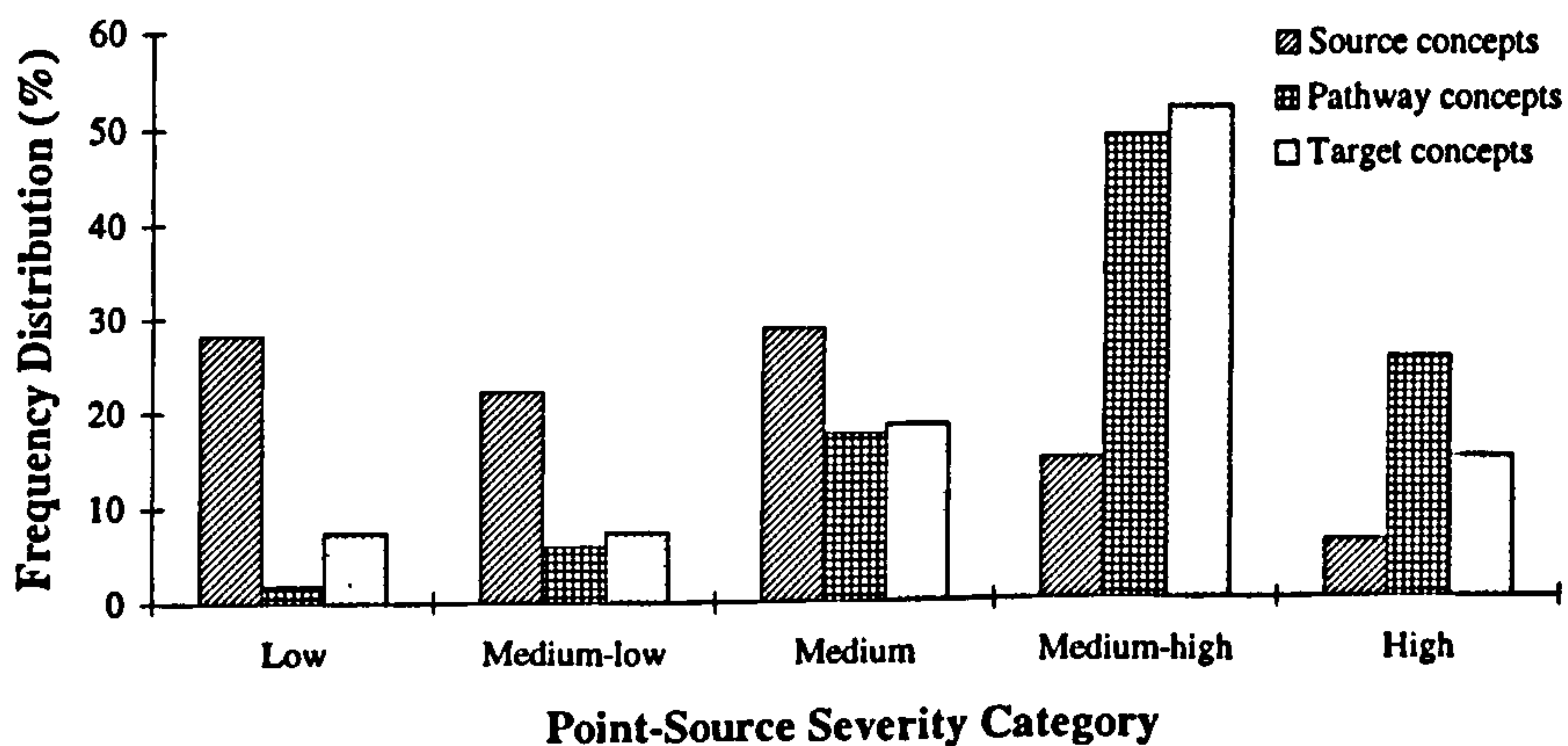
Table 8.10 below shows the frequency distribution of the 228 terms presented to the principal expert (rated with reference to (i) to (iii) above) and equivalent Environment Agency groundwater pollution severity point-source categories (described in Table 2.4, section 2.2.3). Of the 228 terms, 38% were rated either 'medium-high' or 'high' in terms of point-source severity by the principal expert.

Out of a total of 228 terms, 64% were source-based, 24%, pathway-based and 12% target-based. The principal expert rated 26 concepts as being of high significance in terms of point-source severity and another 61 terms as being of medium-high significance. The distribution of

all concepts is shown in Figure 8.13 illustrating the distribution of source, pathway and target concepts.

**Table 8.10:** Frequency distribution of scores obtained by the principal expert in the risk-rating exercise

Rating Score	Frequency	Percentage of total number of terms	Corresponding Environment Agency Point-Source Severity Categories	Percentage of terms in each category
1	8	3.5	Low	19.8
2	15	6.6	Low	
3	22	9.7	Low	
4	13	5.7	Medium-Low	16.7
5	16	7.0	Medium-Low	
6	9	4.0	Medium-Low	
7	19	8.4	Medium	25.1
8	18	7.9	Medium	
9	20	8.8	Medium	
10	27	11.9	Medium-High	26.9
11	18	7.9	Medium-High	
12	16	7.0	Medium-High	
13	13	5.7	High	11.5
14	6	2.6	High	
15	7	3.1	High	



**Figure 8.13:** Distribution of source, pathway and target concept words rated by the principal expert into Environment Agency severity categories for point-source groundwater pollution

The principal expert tended to rate source concepts in the medium and below severity categories whilst rating pathway and target concepts in the medium-high and high categories. Concepts rated into the high significance category by the principal expert included:

*Source-based concepts rated as high significance*

- Type of pollutant e.g. List I substances, petrol spill below ground and diesel spill below ground
- Volume of pollutant e.g. spill/leak > 10,000 litres
- Concentration of pollutant e.g. acute leak

*Pathway-based concepts rated as high significance*

- Unsaturated zone e.g. presence of such a zone, depth to the water table, hydraulic conductivity ( $>10^{-4}$  cm<sup>-s</sup> e.g. sands, gravels)
- Strata type e.g. mainly limestone
- High groundwater flow

*Target-based concepts rated as high significance*

- Potential to affect a drinking water abstraction
- Location of abstraction e.g. drinking water abstraction within 200m

Certain concepts were rated as low significance in terms of risk to groundwater by the principal expert, these included:

*Source-based concepts rated as low significance*

- Site delivery hazards e.g., tanks have overflow protection devices fitted
- Site storage hazards e.g., pipework or tanks with secondary containment, interstitial monitoring of pipework or tanks, cathodically protected pipework or tanks
- Site dispensing hazards e.g., dispensing equipment complies with BS 7117 and pump islands are sealed
- Site control measures e.g., interceptor present and adequate for the site, drainage system can be isolated, site specific contingency plan in place

*Pathway-based concepts rated as low significance*

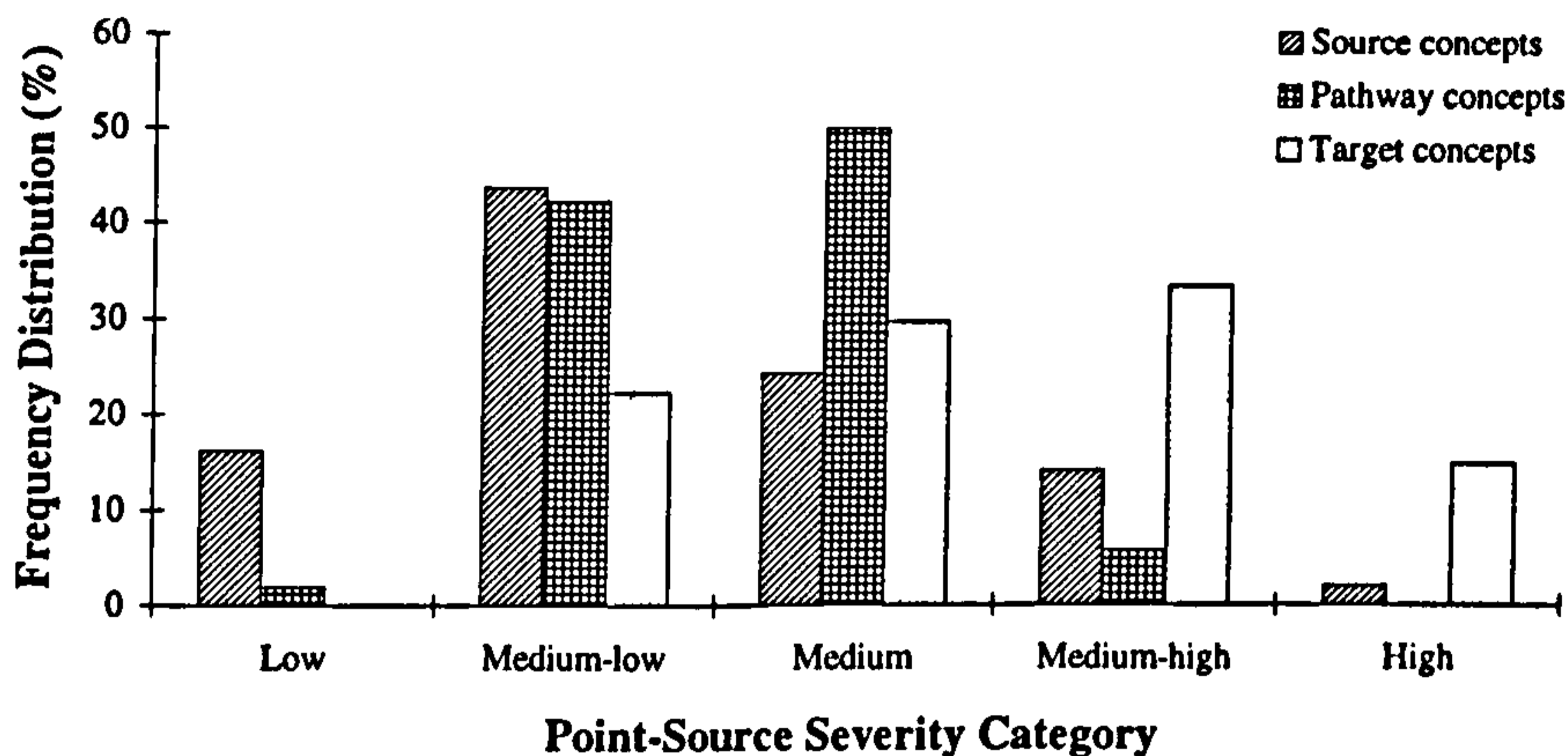
- Presence of tunnels/services e.g., none within 25m of the site

*Target-based concepts rated as low significance*

- Location of targets e.g., no water bodies nearby

The reasons why the principal expert rated concepts as they did are difficult to characterise but may be due to the particular areas of expertise of the principal expert. The principal expert is a regulatory groundwater specialist and as such may have less experience of, and involvement in overall site management issues. A different pattern may of been obtained if the principal expert had been someone with an industrial background before they entered the Agency. The principal expert also tends to be more policy-based and to not be involved intimately in site-specific regulatory matters but is consulted over the more 'difficult' incidents and sites. This is to be expected as the expert is the person with the experience and expertise built up over several years and that expertise is under great demand. There is also the traditional focus of the Agency (and its predecessor body the NRA) on groundwater issues, perhaps leading to an over-emphasis on such matters. However, this would not be unusual as, for example, much of the groundwater protection legislation (EC Directive 80/68/EEC etc.) is focused on groundwater alone and does not give much consideration to other types of target namely humans.

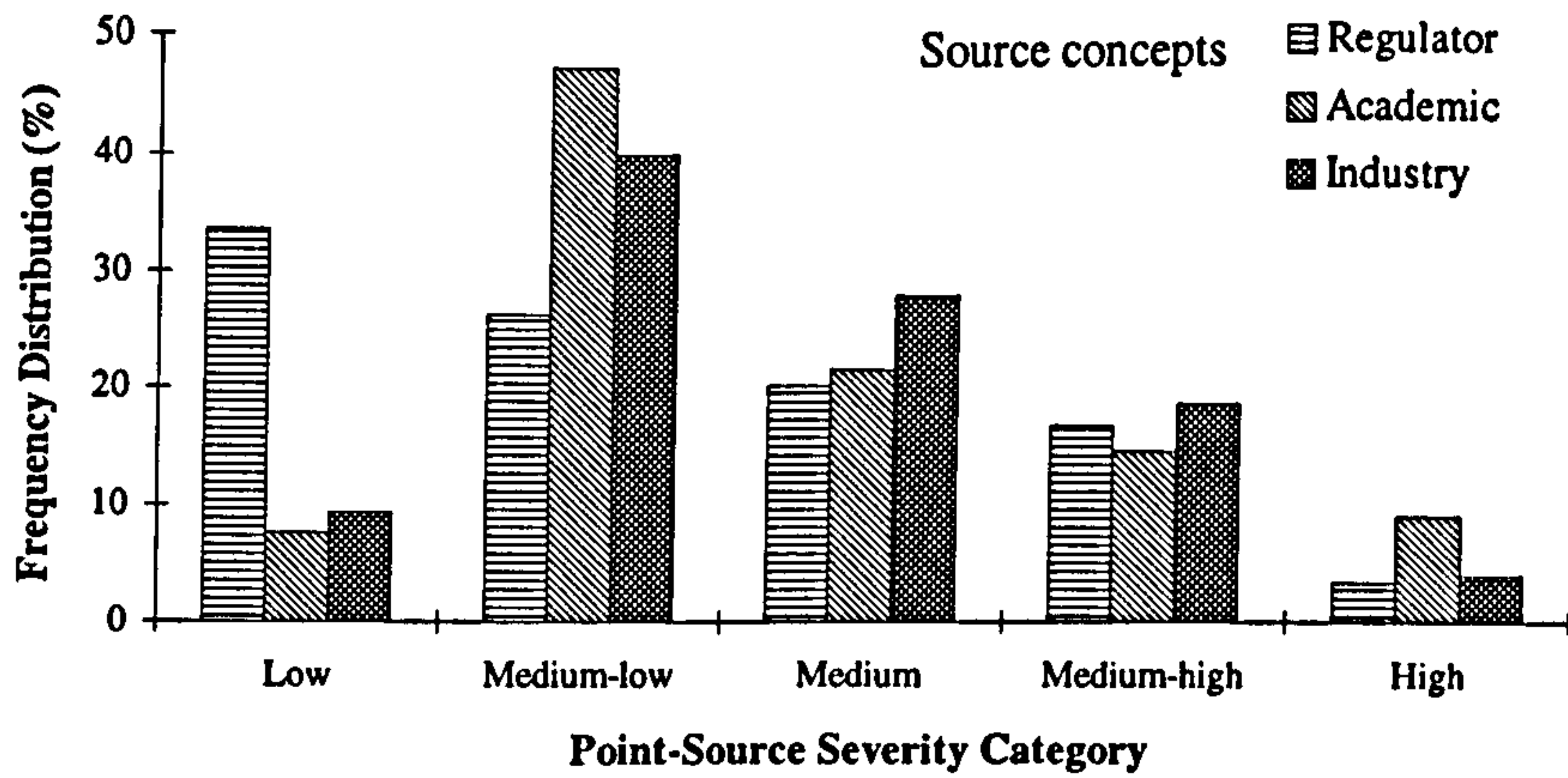
Figure 8.14 shows the results of the risk rating exercise carried out with other participants combined with the results of the principal expert. This shows the frequency distribution of source, pathway and target terms across the five severity categories used by the Agency to classify point-sources of groundwater pollution and gives a different pattern to that shown in Figure 8.13 which shows the results of the principal expert alone - there is clearly a difference.



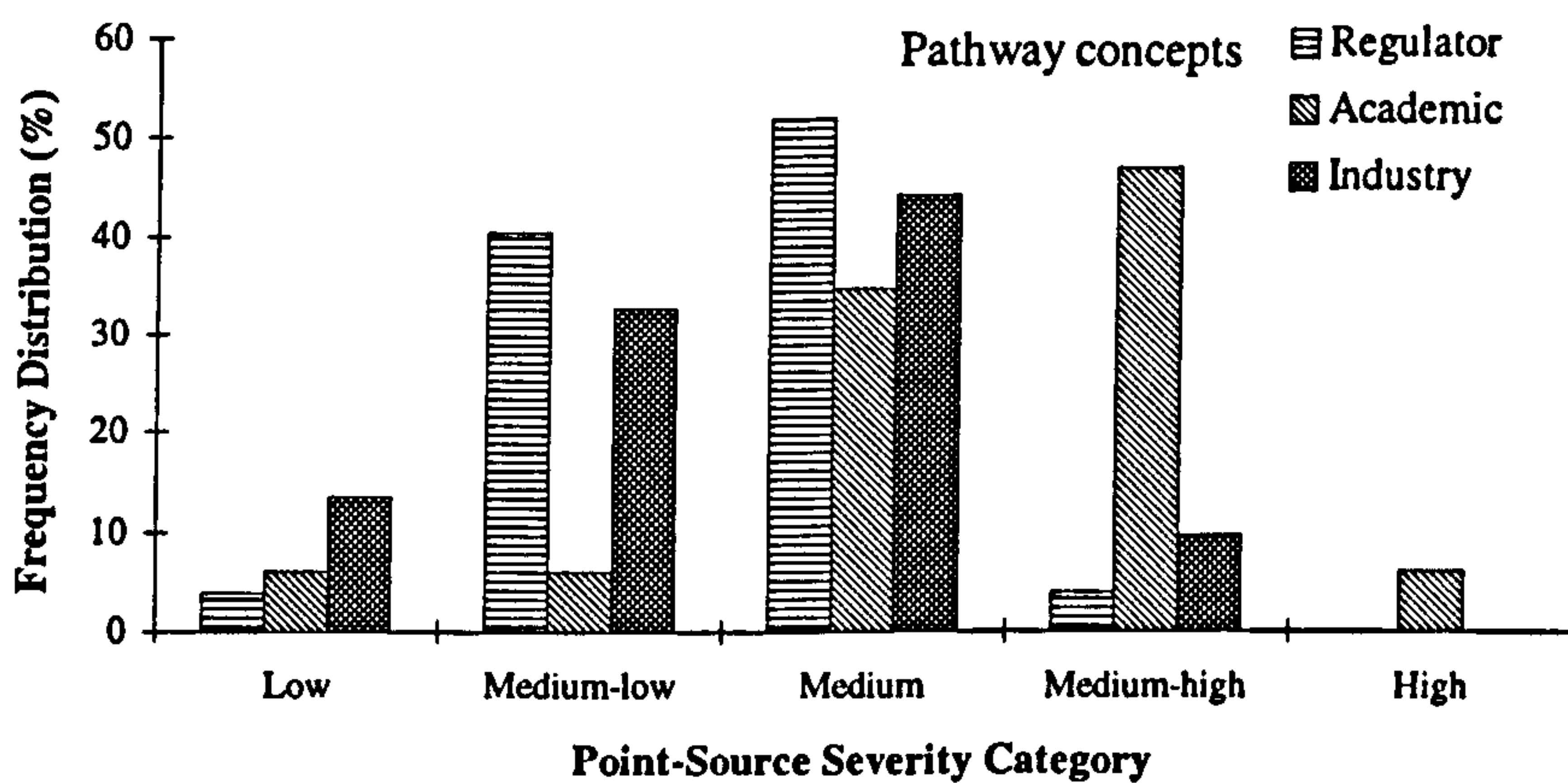
**Figure 8.14:** Distribution of source, pathway and target terms, rated by representatives of the regulatory authorities, academia and industry into Environment Agency severity categories for point-source groundwater pollution

Figure 8.14 shows that source-based terms tended to be rated at a lower level than pathway or target-based terms. There were more source-based terms rated as medium-low (44%) or low (16%) compared to pathway (42% and 2%) or target-based terms (22% and 0%) respectively. For target-based terms, more were rated as medium-high (33%) or high (15%) compared to pathway (6% and 0%) and source-based terms (14% and 2%) respectively. For pathway terms however, the distribution was concentrated in the medium and medium-low categories (50% and 42% respectively). This variation between source, pathway and target terms may be related to the source-pathway-target model and risk-based decision-making itself. For example a source-based term may, or may not, have an impact on whether a pollutant reaches a target, there may be no pathway and/or no target. Similarly with a pathway-based concept there may be no source and/or no target but the pathway term has been characterised in some way. However, with the target-based concept there is definitely a target and it is the target which is the 'risk of concern' be it groundwater itself, or a drinking water abstraction that may impact on humans as a final target. This may lead to the apparent increasing 'importance' of source, pathway and target terms in the eyes of those who participated in this exercise. There may also be 'cultural' reasons for these differences i.e. a difference between regulators, academics etc.

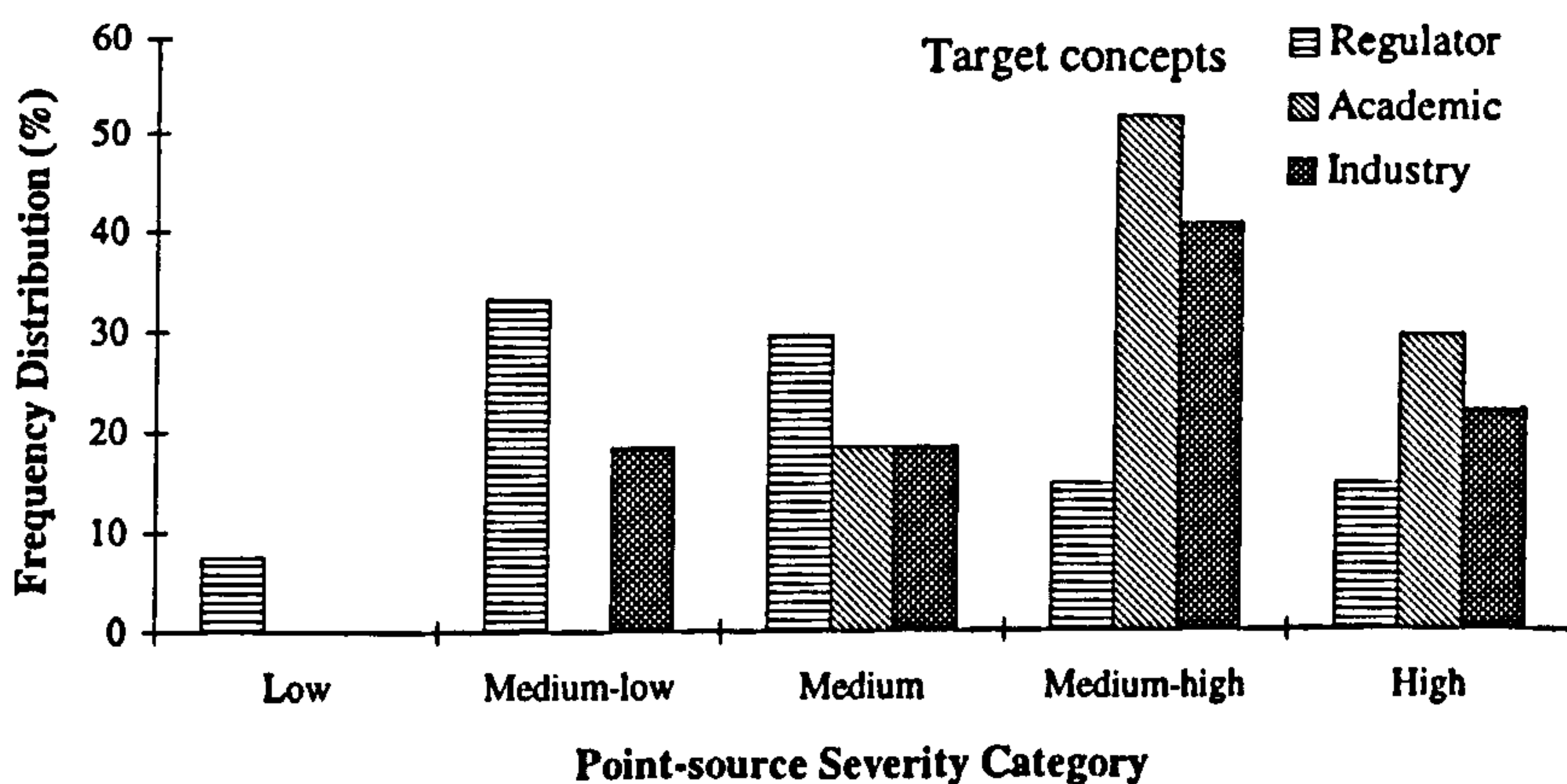
Differences between participants (e.g. differences between Figure 8.13 and 8.14) can be investigated with further analysis. The regulatory representatives were compared to the academic and industry representatives. These results are shown in Figures 8.15, 8.16 and 8.17.



**Figure 8.15:** The distribution of source terms rated by representatives of the regulatory authorities, academia and industry into Environment Agency severity categories for point-source groundwater pollution



**Figure 8.16:** The distribution of pathway terms rated by representatives of the regulatory authorities, academia and industry into Environment Agency severity categories for point-source groundwater pollution



**Figure 8.17:** The distribution of target terms rated by representatives of the regulatory authorities, academia and industry into Environment Agency severity categories for point-source groundwater pollution

Figure 8.15 shows that it is the regulator who categorises more source terms as of low significance when compared to academic and industry participants (over 30% compared to less

than 10%). Academic and industry participants tended to use the 'medium-low' category and not the 'low' category. With pathway terms a different pattern is observed (Figure 8.16). Regulatory and industry participants tended to rate pathway terms in the medium and below categories (regulator rating consistently lower than industry) but academic ratings tended towards the medium and above categories. With target terms (Figure 8.17) regulators were still rating lower but industry had shifted towards the higher significance categories with academics tending even more to the higher significance categories.

Figures 8.15, 8.16 and 8.17 indicate that regulatory participants (which included the principal expert) consistently rated all concepts, source, pathway and target terms lower in terms of risk to groundwater, than other participants. These results do vary from those obtained using the card sort technique although it is difficult to compare the individual results directly. Those taking part in the risk rating exercise could be termed the most skilled participants perhaps enhancing any difference between an academic and a regulatory approach to a problem for example. The regulator is familiar with the terms used in the exercise on a daily and practical basis whereas the academic may not have to deal with them so frequently on a practical basis but has greater theoretical skills and hence takes a more cautious approach as they may understand the full range of potential outcomes. An additional, and potentially complicating factor may be that less individuals took part in the risk rating exercise than the concept sorting.

Those concepts that were rated as high/low significance in terms of the severity of point-source groundwater pollution based on a combination of the principal expert, regulatory, industry and academic representatives have been included in Appendix B.3.

The next chapter describes the generation of the conceptual model used for the basis of the prototype knowledge system. The results presented in this Chapter (particularly the scores obtained for each concept from the risk rating exercise) have been used to generate both the paper and computer-based models.

## CHAPTER 9

### 9 SYSTEM DEVELOPMENT - KNOWLEDGE USE AND REFINEMENT

#### 9.1 INTRODUCTION

This chapter first describes the generation of the conceptual model on which the prototype knowledge system was based. The system itself is then described including system assumptions, limitations, treatment of uncertainty and the outcome of the verification process (where appropriate). The Chapter ends with the system validation process undertaken by potential system users. A detailed critique of the conceptual model and subsequent system is presented in Chapter 10.

A key part of the development process has been system verification. As stated previously, the process of system verification is an iterative rather than isolated stage of development, making the reporting of particular results difficult. A final verification process was undertaken by three people; the principal expert, an Agency hydrogeologist who had taken part in the knowledge acquisition phase and who had a specific interest and knowledge of the area of petroleum groundwater pollution and a second regulatory hydrogeologist from a different Agency Region to the principal expert and who had not taken part in any previous system development stages. This final stage did identify areas for prototype improvement, which are discussed here under the relevant system sections.

#### 9.2 GENERATION OF CONCEPTUAL MODEL

The overall aim of the knowledge acquisition process was to be able to model expert knowledge. Before producing a computer-based representation a paper-based conceptual model is constructed. By producing a visual representation of the decision-making process by means of a series of flow charts, the process becomes more explicit to both the expert and system developer, allowing easier modification (Price *et al.*, 1995).

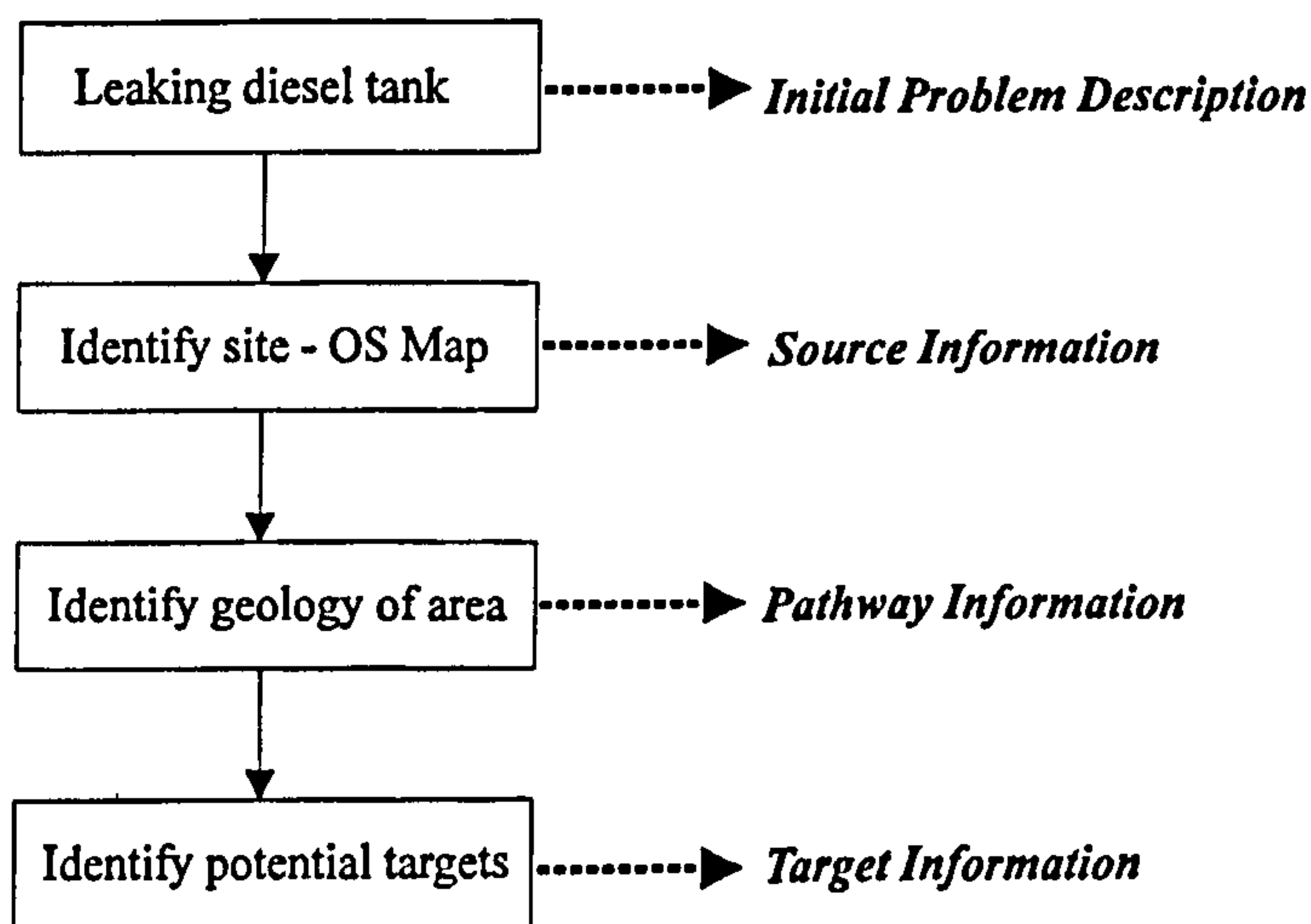
The techniques used and the results obtained from each were described in Chapters 7 and 8, respectively. This process identified information and knowledge that is currently used to assess the risk to groundwater presented by a point-source such as a petrol-filling station. In addition, the user requirements study highlighted information and procedures used by field staff (not necessarily experts) when carrying out such site assessments. Using the results of both these acquisition phases allows a conceptual model to be generated.

Many parts of the decision-making process used by the principal expert are inherently risk-based but this has not been acknowledged previously in any formal way, comments such as "it's gut reaction, it's the way I do it" were recorded. The process of risk assessment as part of



an overall risk management approach to the problem of point-sources of groundwater pollution, was seen as something divorced from what actually happens when decisions are made in the field. Therefore the first stage of developing a conceptual model was to identify the overall steps taken by an expert when presented with a typical scenario of, for example, a leaking fuel tank above a major aquifer. This was carried out in a series of semi-structured interviews with the principal expert, the results of which were reported in Chapter 8, section 8.2.2. The responses made by the principal expert have been used to generate 'process pathways' with regard to the information the expert uses, the order in which decisions are made and how the overall decision-making process could be represented to form a conceptual model. The following flow-charts represent the decision-making process of the principal expert broken down into stages. These stages are somewhat artificial as the expert does not consciously go through each one. However, they provide a valuable visual representation, most importantly demonstrating to a non-expert how the decision-making process operates for the specific problem of a hydrocarbon point-source such as a leaking underground fuel tank. By linking these stages a conceptual model can be built up.

An initial assessment of the leaking tank problem by the principal expert, elicited the following process:



**Figure 9.1:** Preliminary information required by the principal expert when assessing the risk to groundwater from a leaking underground storage tank

The Source-Pathway-Target model was found to be important to the principal expert when assessing a site in terms of risk to groundwater. Figure 9.1 represents the first stage of the process with identification of what information is required. Figure 9.2 illustrates in more detail the types of information required at each of the stages shown in Figure 9.1 and some potential sources used by the principal expert for such information.

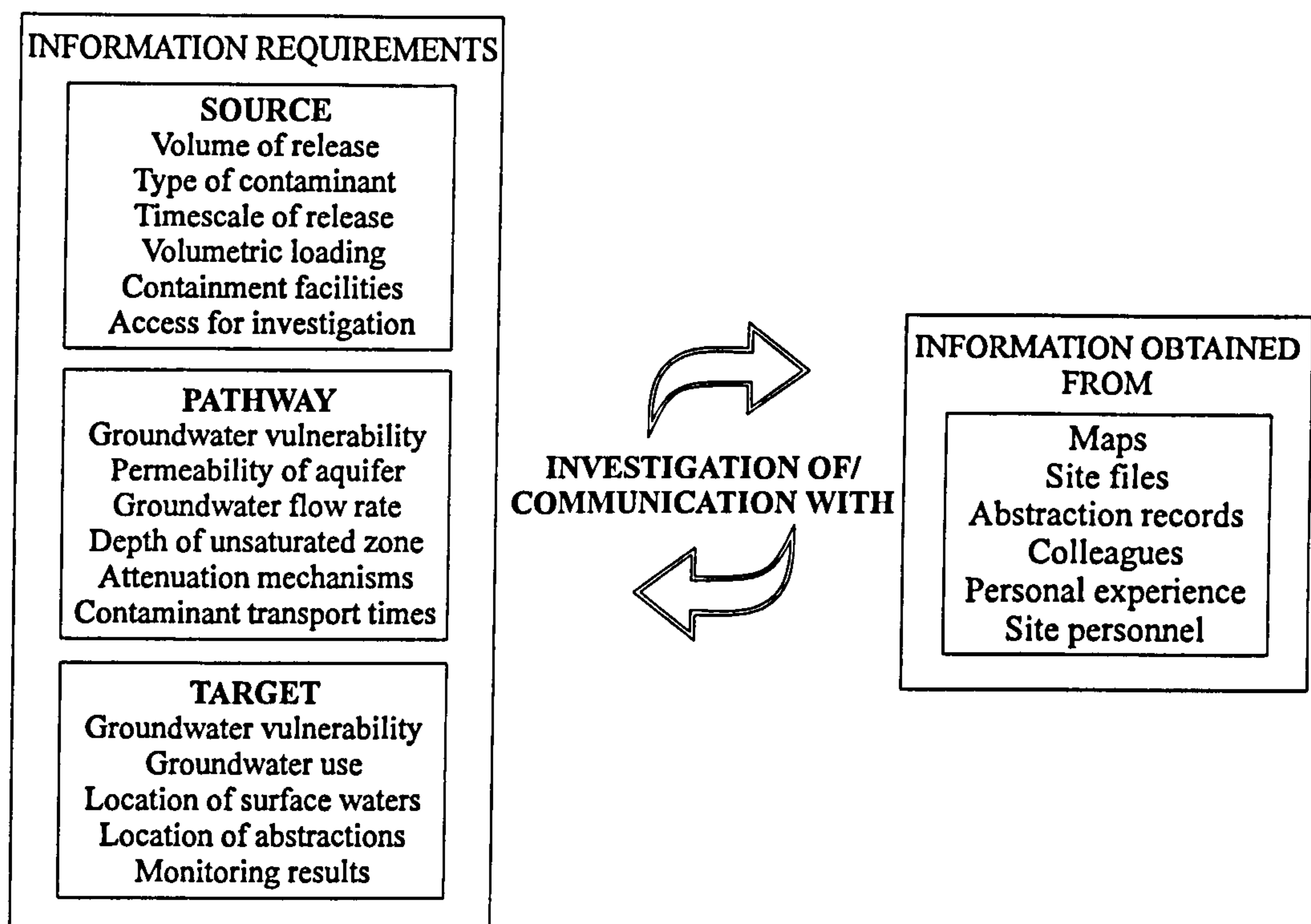
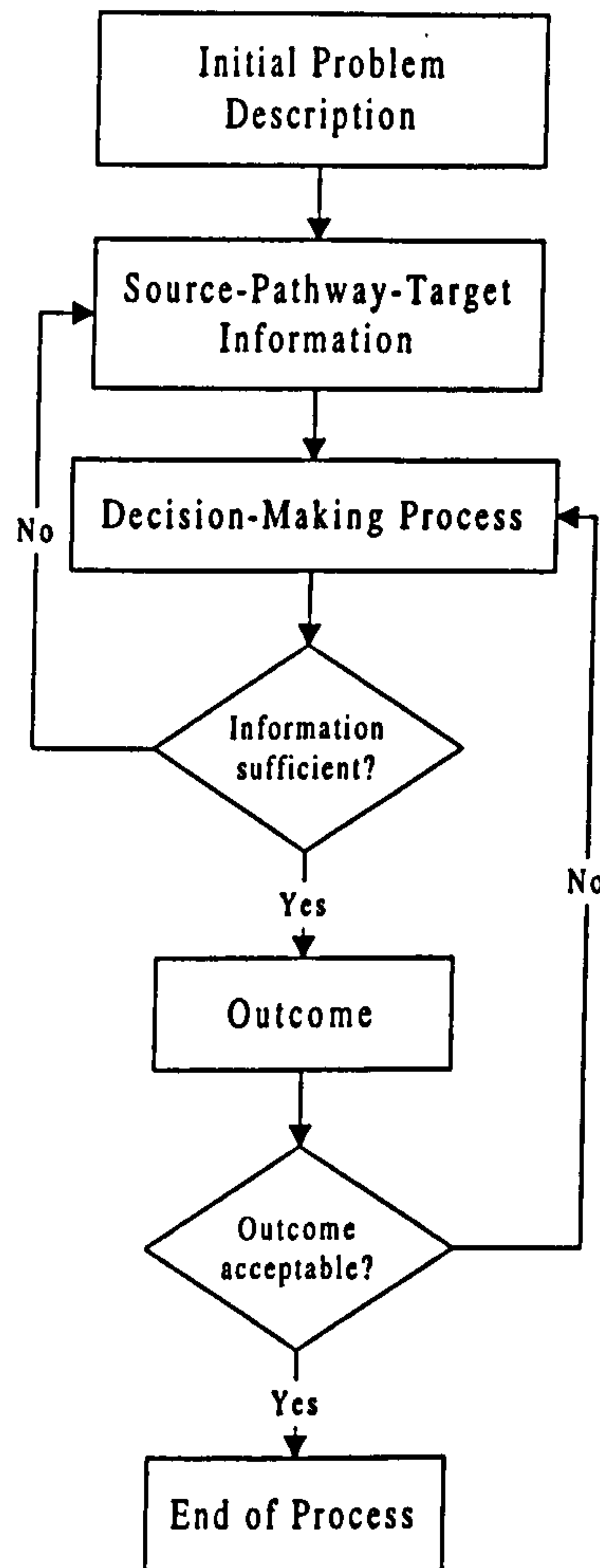


Figure 9.2: Source, pathway and target information requirements

Some of the information requirements shown in Figure 9.2 are relatively easily fulfilled, especially those that rely on the principal expert's own experience, others may be more time consuming and difficult. The expertise lies in being aware of what information needs to be acquired and then how to apply it. The conceptual model must reflect this. The information collected at each stage is represented linearly in Figures 9.1 and 9.2, but in reality is often collected as and when it becomes available and added to the overall assessment in an almost *ad hoc* fashion.

Once the initial problem had been defined and source-pathway-target information had been collated, this information was used to 'feed into' the decision-making process: i.e. what the principal expert was going to do to resolve the problem. Figure 9.3 links Figures 9.1 and 9.2 into that decision-making process.

A 'result' as represented in Figure 9.3 could be many things, for example, a decision to recommend that a certain remediation strategy such as a pump and treat operation be employed at the site. If that option is acceptable in terms of risk to groundwater and to the site operator then that is the end of that particular decision-making process. The same process may, however, be undertaken again if, for example the pump and treat operation is not working properly and further decisions have to be made. In reality the whole process tends to be more cyclical or iterative than linear.



**Figure 9.3:** How source-pathway-target information is integrated into the decision-making process

It is understood that 'model procedures' currently being developed by DETR (Herbert, Harris & Denner, 1995) (but not yet publicly available) for a risk-based approach to contaminated site identification and assessment, favour the use of flow-charts to describe the structured decision process (Petts, 1998).

Target identification and characterisation is, according to the principal expert, the key to the process. Certain factors were felt to be more important than others based on personal experience (some of those factors are shown in Figure 9.2). Driving the decision-making process is the type of target involved. For example, any kind of drinking water abstraction is seen as of paramount importance and a 'worst-case scenario' is assumed, i.e. all of the spilled or leaked fuel is expected to enter groundwater and impact on the abstraction. Simple travel time calculations are used to assess how long before an abstraction could be impacted. The aim is to prevent the pollutant reaching the target or to reduce the consequent impact. This worst-case response reflects the UK regulatory responsibilities. It is recognised that the nature of the target of concern varies in other regulatory regimes - for example, in the USA it is human health as the 'ultimate' target from drinking water.

A drinking water abstraction may not always be identifiable near to a spill/leak but other targets such as agricultural or industrial abstractions and surface water bodies were also considered. Even if none of these can be found, groundwater itself is a target that requires protection (under the European Directive, 80/68/EEC), so a spill/leak will always be investigated, especially if a considerable amount of fuel has been lost (considered to be more than 5000 litres by the principal expert). As stated by the principal expert "gut feeling says that a large spill will have an impact somewhere even if targets have not been identified".

Although target characterisation was considered key to the decision-making process, source characterisation was generally carried out first, for example, what had been released from the tank, how much etc. Any potential targets were then considered and then pathway characterisation was undertaken. The source-pathway-target model although used is turned into the source-target-pathway model.

The 'decision-making process' has been represented in Figure 9.3 as one box flowing into a 'result'. What the principal expert is actually doing is assessing the information collected and deciding what the likely outcome will be: given the source, the pathway and the target how will the target be affected (if at all)? Is that situation acceptable? If not, what actions could be taken? This is the basis of a risk-based decision-making process and is represented in Figure 9.4.

As discussed in Chapter 2, a risk-based decision framework has several recognisable stages:

Stage 1 - Identification of site type (characterisation of the source term)

Stage 2 - Analysis of activities (characterisation of the source term)

Stage 3 - Hazard identification (characterisation of the source term)

Stage 4 - Exposure/hazard pathway (characterisation of the pathway and target term)

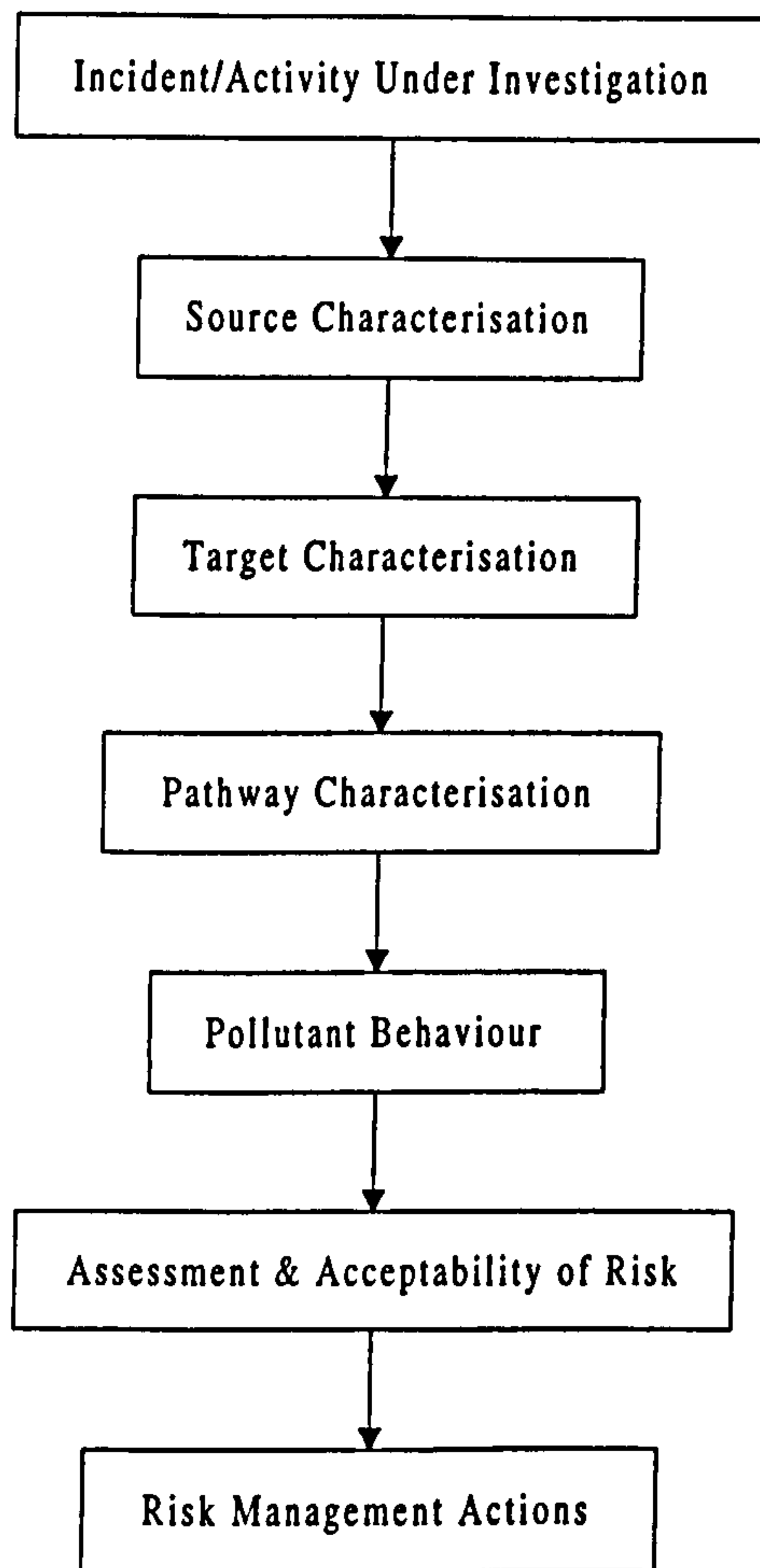
Stage 5 - Prediction of the consequences (characterisation of the pathway and target term)

Stage 6 - Risk assessment calculations (risk estimation)

Stage 7 - Risk acceptability (risk evaluation)

Stage 8 - Risk management actions

The term 'characterisation' has been used in stages 1-5 but in practice can represent something different for each stage from 'identify', 'describe', 'measure' to 'model'. In Figure 9.5, stages 1-8 are overlaid onto the decision-making pathway of the expert in order to describe a conceptual model of the problem. For this information to be developed into a knowledge system, each part of the process must be defined.

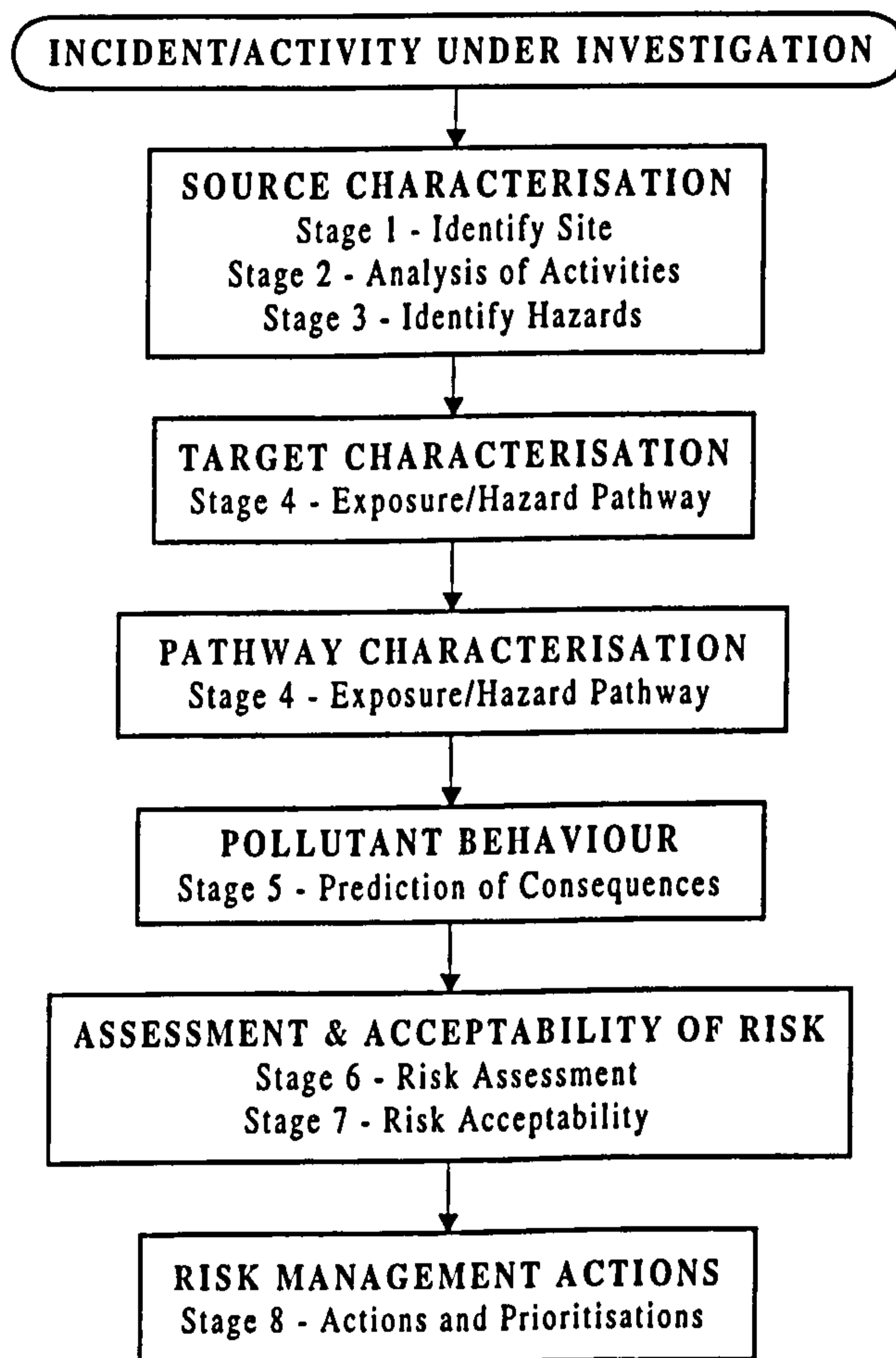


**Figure 9.4:** Risk-based decision-making process of the principal expert

Each section of Figure 9.5 must be broken down to identify exactly which questions need to be asked and what information is required to answer these, before a computer-based model can be developed. Table 9.1 sets out a staged risk management process with the focus on a petrol-filling station. The process itself is based on information elicited during the knowledge acquisition phase of this research. Included in the table are the types of questions that need to be answered and the type of information that non-experts may require as additional explanations of the process or the information requirements as part of the model.

Stage 8 of the risk management process (Figure 9.5 and Table 9.1) is the stage at which management actions must be prioritised. As discussed in Chapter 4, a regulatory body such as the Environment Agency has many responsibilities and often limited resources in terms of finance or the availability of skilled individuals. By using a risk-based approach, sites can be ranked or prioritised in terms of risk to groundwater, ensuring that the decision-making process is logical and systematic and all relevant issues are considered. If an explicit risk-based approach is not used (i.e. no written procedure), some type of site ranking or prioritisation must still be carried out by the decision-maker. This can be done relatively easily by a groundwater specialist with many years experience and could follow a risk-based approach. However, it is

exactly these kinds of decisions that less experienced personnel find difficult. A large amount of complex knowledge is required to make effective decisions, knowing when to discard a piece of information for example. A less experienced person may be over-cautious and rank each source higher than a specialist would. This was supported by results of the concept sorting exercise where 'non-experts' were less inclined than the principal expert to discard concepts as irrelevant (Figures 8.5 to 8.9).



**Figure 9.5:** Overall decision-making process of the principal expert

The Environment Agency has developed a preliminary site ranking scheme for point-sources (Chapter 2, section 2.2.3). Each of the identified 1205 point-sources was categorised into one of five 'point-source severity classes' in terms of significance to groundwater. The basis for classification however, was subjective in nature. The nature of the 'severity' classes was thought to be a useful representation for this research and has been utilised as part of the risk-rating exercise (this was discussed in Chapter 8, section 8.2.5). This exercise provided a 'score' for each concept presented to the principal expert and other participants (shown in Appendix B.3).

**Table 9.1:** A risk management process that could be used to support risk-based decision-making (with a focus on petrol-filling stations as a source of groundwater pollution)

<b>RISK MANAGEMENT PROCESS</b>	
<i>Process Stages</i>	<i>Possible Explanations Required by Users</i>
<b>Stage 1 - IDENTIFY SITE</b>	
<ul style="list-style-type: none"> <li>• Petrol-filling station</li> <li>• Other site types could include: fuel distribution depot, oil storage depot, solvent recovery &amp; storage operations</li> </ul>	<ul style="list-style-type: none"> <li>• Risk-based approach to decision-making, what is risk, stages of a risk-based approach</li> <li>• Description of each site type</li> </ul>
<b>Stage 2 - ANALYSIS OF ACTIVITIES</b>	
<ul style="list-style-type: none"> <li>• Delivery of fuel (from tanker to tank)</li> <li>• Storage of fuel (tanks and pipework)</li> <li>• Dispensing of fuel (tank to vehicle)</li> </ul>	<ul style="list-style-type: none"> <li>• Description of typical activities on this type of site</li> </ul>
<b>Stage 3 - IDENTIFY HAZARDS</b>	
<p><i>Types of Hazard</i></p> <ul style="list-style-type: none"> <li>• Continuous source - e.g. leak from underground storage tank and associated pipework</li> <li>• Discrete source - e.g. spillage on delivery/dispensing of fuel</li> </ul> <p><i>Volume of Pollutant</i></p> <ul style="list-style-type: none"> <li>• Throughput of a site</li> <li>• If a release has occurred, volume of release</li> </ul> <p><i>Type of Pollutant</i></p> <ul style="list-style-type: none"> <li>• Leaded petroleum, unleaded petroleum, diesel</li> </ul> <p><i>Concentration of Pollutant</i></p> <ul style="list-style-type: none"> <li>• If a release has occurred, concentration in soil/water</li> </ul>	<ul style="list-style-type: none"> <li>• Fuel delivery &amp; dispensing system</li> <li>• Typical tank &amp; associated pipework construction, types of material used etc.</li> <li>• Volumes dealt with at a site</li> <li>• Properties of different fuel types</li> <li>• Typical solubilities for each fuel type</li> </ul>
<b>Stage 4 - EXPOSURE OR HAZARD PATHWAY</b>	
<p><i>Identification of Potential Targets</i></p> <ul style="list-style-type: none"> <li>• Presence of abstraction points</li> <li>• Presence of groundwater</li> </ul> <p><i>Geology and Hydrogeology of Area</i></p> <ul style="list-style-type: none"> <li>• Groundwater vulnerability</li> <li>• Presence &amp; nature of soil</li> <li>• Nature of strata, Presence &amp; nature of drift deposits</li> <li>• Depth of unsaturated zone</li> <li>• Groundwater Protection Zones</li> </ul>	<ul style="list-style-type: none"> <li>• Description of typical targets</li> <li>• Understanding of the water cycle</li> <li>• Description of groundwater vulnerability</li> <li>• Soil structure &amp; classification</li> <li>• Definition &amp; examples of strata, drift etc.</li> <li>• Definitions of groundwater protection zones and typical exclusions to development</li> </ul>
<b>Stage 5 - PREDICTION OF THE CONSEQUENCES - HARM</b>	
<p><i>Chemical, Physical &amp; Biological Effects on the Target</i></p> <ul style="list-style-type: none"> <li>• Possible attenuation of pollutant</li> <li>• Physical &amp; chemical characteristics of pollutant</li> <li>• Volumetric loading of pollutant</li> <li>• Link to stage 4 and permeability of strata etc.</li> </ul>	<ul style="list-style-type: none"> <li>• Consequences of groundwater contamination</li> <li>• Describe potential outcomes</li> <li>• Explain significance of strata type, depth of unsaturated zone etc.</li> </ul>
<b>Stage 6 - ASSESSMENT OF ACTUAL RISK</b>	
<ul style="list-style-type: none"> <li>• Possibility of impact on target - presence of a source, a suitable pathway &amp; a potential target</li> <li>• Presence &amp; effectiveness of control measures at source</li> </ul>	<ul style="list-style-type: none"> <li>• Source-pathway-target model</li> <li>• Control procedures may reduce risk to target</li> </ul>
<b>Stage 7 - RISK ACCEPTABILITY</b>	
<ul style="list-style-type: none"> <li>• Having calculated the residual risk (after taking into account any control procedures etc.) is risk to target acceptable ?</li> </ul>	<ul style="list-style-type: none"> <li>• Groundwater protection zones</li> </ul>
<b>Stage 8 - RISK MANAGEMENT ACTIONS</b>	
<ul style="list-style-type: none"> <li>• If risk not acceptable, situation must be managed to reduce the risk to the target with associated monitoring and auditing procedures put in place</li> <li>• If risk is currently acceptable, monitoring &amp; auditing procedures must also be put in place to ensure that risk remains acceptable</li> </ul>	<ul style="list-style-type: none"> <li>• Potential for risk reduction and control measures at source etc.</li> <li>• Explanation for the need for monitoring and auditing procedures</li> </ul>

These scores (and associated severity classifications) can be overlaid onto the relevant section of the conceptual model (Figure 9.5 and Table 9.1). Many concepts can be grouped together to provide a 'scale' of scores. For example, 'solubility of contaminants is high' has a total score of 11.4 and is designated as a medium-high severity concept in terms of significance to groundwater pollution. The terms 'solubility of contaminants is medium' and 'solubility of contaminants is low', have scores of 8.8 and 5.6 respectively (medium and medium-low severity). Therefore scores ranged from 5.6 to 11.4 for 'solubility of contaminants'. These scores have formed a fundamental part of the prototype knowledge system, enabling sites to be ranked and prioritised using a risk-based approach.

There are certain 'parameters' or attributes that must be addressed if a site is to be ranked. Parameters where there is no information must either be ignored or a 'default' value substituted. Using the risk management process from Table 9.1 and a petrol-filling station as an example site, the following parameters could be addressed as part of the process of prioritising the site for action. Information used in this process to define parameters has been supplied by the principal expert and relevant written documents such as the HSE guide to assessing and controlling the risk of explosion and fire at petrol-filling stations (HSE, 1996b) and was presented in Chapters 2 and 3.

#### **Stage 1 - Identify site - Retail petrol-filling station**

#### **Stage 2 - Analysis of activities**

As the site is a retail petrol-filling station several activities are known to take place there such as:

- delivery of fuel
- storage of fuel
- dispensing of fuel

These activities are similar on all sites irrespective of whether the site is placed in a high or low severity category. What differs between them will be the potential or actual impact on groundwater that each site may have due to differences in location, site management, quantity of fuel stored etc.

#### **Stage 3 - Hazard identification or Characterisation of the Source.**

This stage can be further broken down into hazard type.

##### *Product Hazards*

Type of product on site e.g., petroleum, has a higher solubility in water than diesel and is more likely to be able to move through the rock matrix

Volume held on site e.g., large operational volume of >100,000 litres with a high site throughput > 5 million litres per year

##### *Delivery Hazards*

Tank-fill method e.g., tanks can be directly filled from a tanker where overfilling could occur or be driven away before off-loading is complete



Ground conditions e.g., area around the fuel delivery area could be in a poor condition with cracked areas, providing a route for spilled fuel to escape from the site into the ground

*Storage Hazards*

Tank position e.g., underground (harder to inspect)

Tank construction e.g., single-skinned steel, no provision for any secondary containment

Tank age e.g., >30 years, older tanks especially those made of steel are more likely to fail

Pipework age e.g., > 30 years, as with tanks the older the pipework the more likely it is to fail. In addition, pipes are more likely to fail than tanks of the same age

Leak detection system e.g., manual tank dipping is an inherently unreliable method of checking for leaks/spills

*Dispensing Hazards*

Dispensing pump standard e.g., non-standard pump in use

Ground conditions e.g., area around dispensing area cracked and in a poor condition

Fuel delivery system e.g., fuel can be delivered by a pressurised system where fuel will continue to be delivered even if a pipe fails

*Control Procedures*

This information can be used at a later stage to assess residual risk

Site drainage and interceptor system e.g., drainage may rely on a soakaway system with no interceptor. The system can be isolated and may not be tested regularly

**Stage 4 - Exposure or Hazard Pathway - Target and Pathway Characterisation**

*Target characterisation*

Target type e.g., identification of a drinking water abstraction borehole within 1 km

Other target types present e.g., surface water bodies with water quality objective (a)

*Pathway characterisation*

Groundwater protection zone e.g., zone I requires highest level of protection

Permeability of aquifer/unsaturated zone e.g., high permeabilities such as found with sands/gravels could provide for less attenuation of any release before reaching the water table in the case of permeability of the unsaturated zone and in the case of aquifer permeability allow for greater movement of any release

Depth of unsaturated zone e.g., < 5m may provide for less attenuation

Strata type e.g., limestone, often highly fissured with associated high permeability allowing greater movement of fuel

Groundwater flow e.g., a high flow will allow any contaminant plume that does form, to move greater distances

Groundwater vulnerability e.g., if site is located on a known major aquifer, greater protection is required

A site with the example attributes described above would be classified as a high severity site.

A site with different attributes - for example, on a non-aquifer, with state-of-the-art site control

procedures etc. - may be classified as of medium-low severity in terms of risk to groundwater. The key point is that there is a scale from high to low which can be applied to each attribute to provide a 'score', and it is the relationship between these scores that is important, not necessarily the number itself. In this research the scores have been obtained from the risk rating exercise on a semi-quantitative basis (discussed in the next section) rather than the qualitative basis used by the Agency in their original rating procedure.

The formation of a conceptual model (Figure 9.5) and the development of an outline for a site ranking or prioritisation system leads into the final stage of prototype knowledge system development. This final stage discusses the actual construction of a computer-based model which was then evaluated (sections 9.3 and 9.4, respectively). A discussion and critique of the model is found in Chapter 10.

## **9.3 DEVELOPMENT OF COMPUTER-BASED PROTOTYPE**

### **9.3.1 System Development Platform**

As discussed in Chapter 7 (section 7.3.1) a shell environment was considered the best development option for this research. The commercially available shell called ESTA (Expert System for Text Animation) marketed by the Prolog Development Center was selected. ESTA became available commercially in 1993 (so would not be considered 'new' in software terms) and has been developed using the language PROLOG. A development manual is supplied with the software and a telephone helpline is available. Using ESTA as development software, allows the generation of a prototype knowledge-based system that can be used as a decision-support system, without significant programming skills on the part of the developer and relatively quickly (Prolog Development Center, 1993). This approach was ideally suited to this research, as it was the application of the technology of knowledge systems that was being investigated not the development of a knowledge system *per se*.

ESTA uses a Windows environment and can be interfaced with other applications such as Microsoft Excel. In addition, any system developed can be extended and improved by using PROLOG directly (if a licensed copy of the PROLOG language is available). This allows ESTA to act as a prototyping tool. The knowledge base developed with ESTA is rule-based and is shown as a tree-representation, the branches clearly showing how the knowledge is arranged. Errors made when inputting material are automatically detected and are pointed out to the knowledge engineer. Hypertext linkages and bitmap pictures (and photographs) can also be incorporated into the system. The user interface is generated automatically, and an explanation facility for the user can easily be incorporated (an important consideration as potential users may not be frequent users of computer-based tools). Development of a prototype knowledge system using ESTA is a logical step-by-step process based on sets of rules, facts, parameters and control statements.

### *Set of Rules*

An example of a rule is:

IF there is a Source (petrol-filling station) THEN check to see if there is a Pathway

IF there is a Pathway THEN check to see if there is a Target

IF there is a Target THEN the Source may present a risk to groundwater.

By defining and using relevant parameters, these rules can be evaluated. Within ESTA this process is controlled by 'control statements', including any 'set facts' and any further rules.

### *Set of Facts*

Facts in this context include information that remains constant from site to site i.e., information that is independent of a specific site. This could include the fact that 'petrol is a hydrocarbon' for example.

### *Set of Parameters*

A parameter is a variable (as opposed to a 'fact') and the value of a parameter can change, depending on the situation under investigation (i.e., site dependant). Parameters receive values during a consultation via questions to the user and/or are assigned values by rules. An example parameter that requires a response from the user, would be an answer to the question 'Do the tanks have an over-fill protection device fitted' ? The answer could be 'yes', 'no' or 'unknown'. This would be represented in ESTA syntax as:

Parameter over\_fill: 'Is there an overfill-protection device fitted'

type Boolean

question 'Do the tanks have an over-fill protection device fitted ?'

The ESTA shell defines several types of parameter. The example above shows a 'Boolean parameter', the answer being 'yes', 'no' or 'unknown' (true or false). A 'number parameter' can be defined where ESTA requires a numerical answer to be input by the user (or defined by a rule). The third type of parameter is a 'category parameter' where the user is presented with a list of choices (not just yes or no). For example, if the question put to a user was 'How are the tanks constructed ?' and the options available were 'single-skinned steel', 'double-skinned steel', 'glass-reinforced plastic', 'steel with a polyurethane jacket' or 'unknown' then this could be represented in ESTA as a parameter called 'tank\_construction' as follows:

parameter tank\_construction : 'evaluate type of tank construction on site'

type category

options

single\_steel - 'Single skin steel tanks ',

```
double_steel - 'Double skin steel tanks ',  
grp - 'Glass Re-inforced Plastic tanks ',  
steel_poly - 'Steel tanks with a polyurethane jacket ',  
unsure - 'Not sure'.
```

```
question 'How are the tanks at 'site_name' constructed ?'
```

The user is asked the question and presented with the list of options to choose from. Parameters are not evaluated at random and it is necessary to link the various parameters together. This is achieved by control statements, which are used by ESTA to direct how the system will function.

### *Set of Control Statements*

These are statements used to decide which part of the system or which parameter to evaluate next and they are called 'sections'. ESTA works sequentially through each section until a parameter is reached that has not been evaluated, i.e. it has no value assigned to it yet. That parameter is then evaluated before the system moves on to the next section. The first section in an ESTA knowledge-base is always called 'Start'. This may contain 'advice' which is text ESTA will display onto the screen, such as a 'welcome message'. As part of the 'Start' example below, the parameter 'site\_type' must be evaluated and the question 'What type of site are you investigating?' with a list of options will be presented to the user. This is written in ESTA as:

```
Section start: 'main start section'  
advice 'Hello and welcome to this consultation session'  
if (site_type = petrol_filling_station) do petrol_filling_station  
if not (site_type = petrol_filling_station) do other_sites
```

The parameter to be evaluated is 'site\_type'. If the user chooses 'petrol-filling station' from the list presented to them, then the system moves onto the section called 'petrol\_filling\_station' and further questions about the site. If the user chooses a site type other than petrol-filling station, then the system moves onto the section called 'other\_sites'.

The overall structure of the knowledge-base can be illustrated by drawing up a 'section-tree'. An example section-tree is shown in Figure 9.6 (the full section-tree for the prototype system developed as part of this research is shown in Appendix C.4).

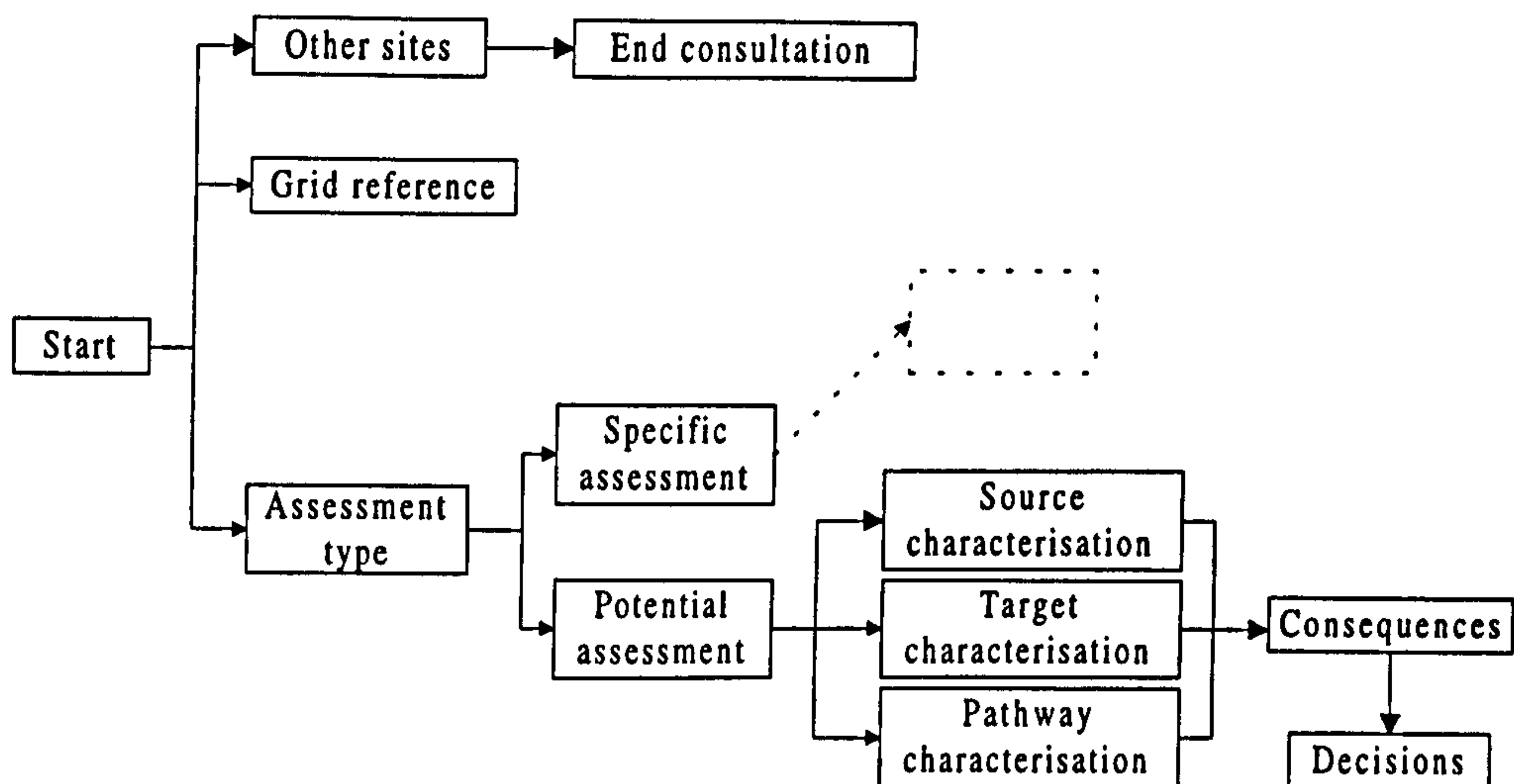


Figure 9.6: Example section tree from ESTA

### 9.3.2 Development of HARRIS - Hydrocarbon and Risk Related Information System

This section describes how the information acquired during the knowledge acquisition process and used to develop the conceptual model (on paper) described in the previous section, has been further used to develop the computer-based prototype. For ease, the presentation is of a linear development process although in practice it is highly iterative.

Figure 9.5 (section 9.2) represents the overall conceptual model, demonstrating the stages that an expert would go through when assessing a site, based on the Source-Pathway-Target model. However, as identified the process the expert actually follows is Source-Target-Pathway. The various stages of a risk management process have been overlaid onto this and it is these stages that have been used to provide a framework for the prototype, also broadly defined in terms of Source-Target-Pathway. The rationale behind the inclusion of each parameter, the order they are considered, and in particular how uncertainty has been managed (choice of worst-case scenario or not) can be found in Chapter 10.

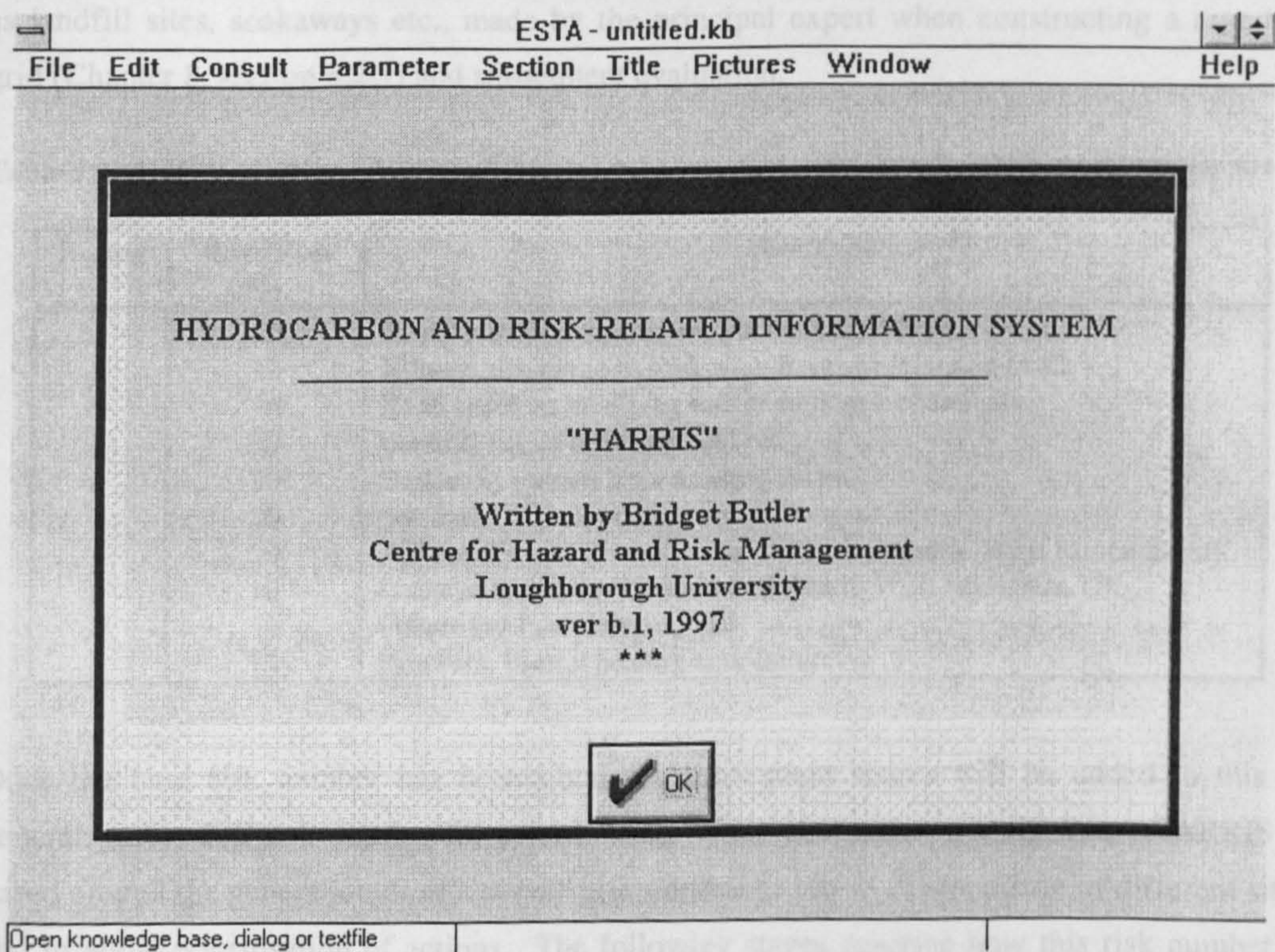
The knowledge system developed as part of this research focuses on hydrocarbon point-sources such as petrol-filling stations and has been designed to support risk-based decision-making. It has been called HARRIS - Hydrocarbon and Risk Related Information System. When the user starts to use the prototype system (HARRIS) they are not confronted with a series of flow-charts to work through but are guided through a session by HARRIS asking a series of questions, the answers to which denote what HARRIS does next. When the user begins a session, the first screen is a 'title screen', shown in Figure 9.7

To start the system, the user must 'Begin a consultation' with HARRIS. The user is then introduced to the system; what HARRIS is and what it will, and will not, do and given some

basic operating instructions. Once through these initial screens an actual site assessment can begin based on the 8 stages discussed in section 9.2.

The decision-making process represented by HARRIS is demonstrated in Figure 9.8 (shown at the end of this section) as a flow-chart but is first described in detail below as it is presented to the user. The information requirements of HARRIS are described in Appendix C.1 with example outcomes (best-case, worst-case and uncertain scoring scenarios) for prioritisation shown in Appendix C.2. Much of the information required by HARRIS would be available from a desk-study, however, a short site visit would provide the opportunity to collect more accurate information, from the site operator for example. Whilst HARRIS can be used without a site visit as 'uncertain' answers can be dealt with, a site visit is recommended.

After the initial instruction screens the user is asked to provide a name and location for the site under investigation. This is to provide a record of the investigation at a later date. The user is then asked to select a 'site type' that best describes the site they are investigating and characterisation of the site begins.



**Figure 9.7:** Title screen of HARRIS - Hydrocarbon and Risk Related Information System

### *Stage 1 - Identification of Site Type - Characterisation of the Source Term*

Although HARRIS was designed specifically for the assessment of retail petrol-filling stations, the overall structure of the assessment model and prototype system has been designed to enable

further site types to be included in the future if required. These might include:

- Fuel distribution depot
- Oil storage operation
- Oil recovery operation
- Solvent storage operation
- Solvent recovery operation

Currently, if the user chooses any option other than 'petrol-filling station' the consultation session ends with a screen explaining the current site limits of HARRIS. The user is then given the option of trying another consultation.

If the user does choose 'petrol-filling station' then the next screen introduces the concept of a 'risk number' for the site. The 'base risk number' is that number than can not be reduced by, for example, introducing improved engineering procedures to reduce risk to groundwater. It has been set at 10 for petrol-filling stations. This figure (illustrated by examples in Table 9.2) has been compiled from the comparisons relating to 'overall risk to groundwater' from sources such as landfill sites, soakaways etc., made by the principal expert when constructing a repertory grid (Chapter 8, section 8.2.1) and subsequent evaluation.

**Table 9.2:** Rating of various site types in terms of risk to groundwater with resulting 'base risk numbers'

Rating	Base Risk No.	Site Type
1	50	Major chemical factory on Sherwood sandstone
2	40	Effluent discharge to soakaway from renderers on chalk
3	30	Road accident involving tanker spillage - chemicals
3	30	Landfill site in opencast coal pit
3	30	Soakaway system from housing estate
3	30	Sewage sludge spreading on chalk
4	20	Redevelopment of steelworks in Black Country, West Midlands, UK
5	10	Leakage from petrol station in Solihull, West Midlands, UK
5	10	Pulverised Fuel Ash disposal
5	10	Domestic central heating tank failure

Once the base risk number has been obtained, subsequent scores will be added to this to generate an overall risk number for prioritisation of the site under investigation. HARRIS is based around the generation of this overall risk number to allow a comparison of different sites and to allow prioritisation of actions. The following stages describe how this risk number is generated with respect to the information obtained from the user and that already contained in the HARRIS knowledge-base.

The user is then asked for a grid reference for the site under investigation. This information is for recording purposes only and is not part of the assessment but can be used to keep track of

any consultations undertaken with HARRIS. Ultimately it could be used to link to other geographic information such as groundwater vulnerability maps via a GIS.

The next step is the choice of the type of assessment is to be made:

- (i) *ex-post* - i.e. assessment of an actual incident (such as a diesel spill) in terms of risk to groundwater; or
- (ii) *ex-ante* - i.e. assessment of the whole site in terms of potential risk to groundwater.

This is an important decision which must be made at the start of any assessment. The type of information that may be needed to assess the risk from an actual incident (*ex-post* assessment) is different in many respects to the information needed when there is no particular incident to be investigated (*ex-ante* assessment). For example, when investigating a specific incident the volume of material that has been released is an important parameter but when assessing the site *ex-ante*, the storage volume would be more appropriate.

Although a facility for investigating specific incidents has been included as part of HARRIS at this prototype stage it has not been developed fully. It is the *ex-ante* whole site assessment for potential risk to groundwater that has been developed to provide a decision-support system for prioritising sites and particular risk management actions.

### ***Stage 2 - Analysis of Activities - Characterisation of the Source Term***

Petrol-filling stations have well-defined activities, such as:

- Fuel delivery
- Fuel storage
- Fuel dispensing

The system assumes that each of these take place. If the system were to be extended, this section would have to be modified to take into account the relevant activities that may occur at a different type of site.

### ***Stage 3 - Hazard Identification - Characterisation of the Source Term***

Full characterisation of the source term is the first step, followed by target and pathway characterisation. As HARRIS is not a predictive system, the user will not be using it if there is no source term identified. Hazard identification has been broken down into the categories shown below to satisfy the data requirements of HARRIS. It should be noted that HARRIS uses expert knowledge to handle data from the user and is able to infer certain things. For



example the user must supply HARRIS with the type of material stored at the site, petrol, diesel etc. HARRIS can then utilise knowledge encoded in the rulebase to assign scores based on solubilities, half-life in groundwater etc.

- Hazards associated with type of products (or pollutants) at the site - Product hazards
- Hazards associated with delivery of petroleum to the site - Delivery hazards
- Hazards associated with storage and distribution of petroleum at the site - Storage hazards
- Hazards associated with dispensing of petroleum to the customer - Dispensing hazards
- Site Control Procedures - strictly speaking these are often risk reduction measures and should be taken into account at Stage 6 but in terms of a system structured in a logical manner for the user, all 'source-based questions' come together.

### *Product Hazards*

The user is asked what type of product is sold from the site as petroleum, diesel or other products. Table 9.3 (and those following) show what the respective scores or 'risk numbers' have been assigned for each parameter. The magnitude of these scores has been obtained from the risk rating exercise (Chapter 8, section 8.2.5).

**Table 9.3:** Type of product stored at a site, showing associated risk numbers

Product Type	Yes	No	Not sure
Diesel	11.6	0	11.6
Petroleum	12.2	0	12.2
Other Products	8.6	0	0
Totals	32.4	0	23.8

The issue of potential groundwater polluting impact of petroleum as opposed to diesel was raised during system verification. The principal expert felt that diesel was more toxic and a higher risk to groundwater than petroleum. As discussed in Chapter 3, the exact composition of a particular fuel is difficult to elicit, as the information is commercially confidential. There are certain regulatory controls and standards used to govern the composition of fuels but these are often represented as maximum/minimum concentrations of the main fuel constituents (e.g. Table 3.2). However, diesel is less soluble in water than petrol (< 1ppm as opposed to 50-100 ppm) and has a higher viscosity, so if released into the soil it will migrate but at a slower rate than petrol (Cole, 1994: p66). Diesel also contains less benzene (important in terms of carcinogenic risk to humans) than petrol (Morgan & Swett, 1994). Petroleum can contain lead or other additives (such as MTBE which is more soluble in water than the other components of petrol e.g. BTEX) and may be more persistent (e.g. Squillance, 1995; Turrell *et al.*, 1996, Chapter 3, section 3.3). Petroleum represents the larger share of the total fuel market (commercial and retail). For example, in 1996 total petroleum sales in the UK was 22,216,259

tonnes compared to 14,4379,992 tonnes of diesel (Chapter 3, Table 3.3). However, the petroleum licensing regulations governing tank licensing by the local Fire Brigade (or Civil Defence Authority) do not apply to diesel tanks, which may mean that there will be more leaks from diesel tanks due to a lack of regulatory control. Consequently the 'scores' used for diesel and petroleum as part of the prototype system were similar at 11.6 and 12.2, respectively.

If a user does not know what kind of product is stored at the site, the system will score the question for them. In terms of diesel storage, approximately 5% of retail petrol-filling stations in the UK do not sell diesel (IOP, 1997b) so the most likely scenario is that the site *does* store diesel and hence the score of 11.6. The number of retail sites not selling petroleum is very small, so the chances are that the site will store petroleum and a score of 12.2 is allocated. Other products which may be stored at a retail petrol-filling station include mineral oil. Oil may be stored in underground or above-ground tanks and if present should be included as a potential source of groundwater pollution. However, unlike petroleum or diesel, the majority of retail sites do not store products such as mineral oil in large quantities so an unsure answer will score '0'.

If a particular release was under investigation it would be important to know what had been leaked or spilled. Fuel delivery statistics for the UK retail market show that unleaded petroleum forms approximately 55%, followed by leaded petroleum at 25% and diesel at 20% (Figure 3.4). Therefore if the product type is unknown it is more likely to be petroleum than diesel but if it is known to be petroleum, it is twice as likely to be unleaded (with the possibility of an associated MTBE release) as opposed to leaded fuel. HARRIS does not currently distinguish between leaded and unleaded fuel but could be adapted to take this into account. The presence of additives such as MTBE for example, could be important, especially if MTBE is used to trace the extent of a potential contaminant plume (MTBE being more soluble than BTEX compounds). If there was no MTBE present in the product it would not be present in any plume and checking for MTBE would not provide useful information about whether a release had occurred or not.

The following scoring scale can be generated for fuel type:

No products (0) Other products only (8.6) ⇒ Diesel only (11.6) ⇒ Petroleum only (12.2) ⇒ Unsure (most likely is petroleum + diesel but not other products) (23.8) ⇒ Petroleum + Diesel (23.8) ⇒ Petroleum, Diesel + Other products (32.4)

Originally the user was questioned at this point about whether any previous incidents had occurred at the site under investigation e.g., previous spills or leaks of fuel, possibly with a known impact on an identified target such as a drinking water abstraction point. It was felt that this section of HARRIS was out of place and should form part of the target characterisation section and was therefore moved. Reasons for this were based on the source-target-pathway

model of assessment and asking the user to consider a target concept whilst characterising the source was considered to be confusing.

### *Delivery Hazards*

There are several different methods of delivering fuel from a tanker to the tank such as 'direct - fills' or 'off-set' fills (Chapter 3, section 3.3.1). A direct fill to a tank provides for the lowest control and the tank can easily be damaged or over-filled and a spill occur. Delivery points on most sites in the UK are now 'off-set', away from the fuel dispensing area. This allows for the off-set fill area to be bunded if it is above ground or contained in a chamber if below. Therefore, the following scores are assigned:

Off-set fill above ground and bunded (3.8)  $\Rightarrow$  Off-set fill below ground, with secondary containment (4)  $\Rightarrow$  Unsure (6)  $\Rightarrow$  Off-set fill, below ground, no secondary containment (6.2)  $\Rightarrow$  Off-set fill above ground, no bunding (6.4)  $\Rightarrow$  Direct fill (6.6)

A user may not know what type of fill system is in use at a site so assumptions must be made. It is not known what the distribution of each fill-point type is in the UK so in cases of uncertainty, rather than taking the worst case scenario, a 'half-way stage' is described (the reasoning behind such decisions is discussed further in Chapter 10). The scores range from 3.8 to 6.6 for this part of the calculation, a range of 2.8 points. Half of this would be 1.4, by adding this to the lowest score of 3.8, the mid-point is a score of 5.2.

Tanks may also have 'over-fill protection devices' (OFPD) fitted to prevent a tank from being overfilled. There are several different varieties but it is likely that they are relatively common at UK retail sites. Therefore if an OFPD has been fitted a score of 3.2 is allocated, 6 if there is no OFPD and as OFPD's are relatively common an 'unsure' answer is scored 3.2.

The final question related to fuel delivery is about the concrete pad where deliveries take place. A pad in good condition with no visible cracks etc. is scored 4.8 and in poor condition, 8.2. When HARRIS was evaluated by the principal expert an unsure answer to this question was scored at 6.5 i.e. mid-way.

### *Storage Hazards*

Operational tank volume is a storage related parameter that can be used when assessing the whole site for potential risk to groundwater - the more product is stored, the larger the potential source term may be. For HARRIS, operational tank volume > 100,000 litres, scores 5.6, 50,000 to 100,000 litres, 5.2 and < 50,000 litres, 4.8. If the user is not sure what the operational volume is, HARRIS will assist the estimation by asking a further question on site location. Operational tank volume can be linked to site throughput (although this is not necessarily

always the case). Sites on motorways or major routes tend to be high throughput sites so score 5.6, town or supermarket sites will tend to have a medium throughput and score 5.2, while rural sites or those on more minor routes will tend towards lower throughput and score 4.8.

Tank construction is another significant parameter (discussed in Chapter 3 - section 3.3.1). Tanks are usually constructed from steel or GRP but can also be further protected by being double-skinned or corrosion protected (steel only). Table 9.4 shows the range of tank constructions and related scores used by HARRIS.

**Table 9.4:** Tank construction and associated protective measures - with associated HARRIS scores

Tank Type	Risk no. for Tank	Risk No. for Corrosion Protection	Total Risk No.
Single skin steel, no cathodic protection	5.8	3.2	9
Single skin steel, with cathodic protection	5.8	1.6	7.4
Single skin steel, not sure about cathodic protection	5.8	3.2	9
Double skin steel, no cathodic protection	3	3.2	6.2
Double skin steel, with cathodic protection	3	1.6	4.6
Double skin steel, not sure about cathodic protection	3	3.2	6.2
Glass Reinforced Plastic (GRP)	4.4	-	4.4
Steel with polyurethane jacket	2	-	2
Unknown tank construction	5.8	3.2	9

This gives the following scoring scale:

Steel with polyurethane jacket (2) ⇒ GRP (4.4) ⇒ Double skin steel + corrosion protection (4.6) ⇒ Double skin steel, unsure about corrosion protection (6.2) ⇒ Double skin steel, no corrosion protection (6.2) ⇒ Single skin steel + corrosion protection (7.4) ⇒ Single skin steel, no corrosion protection (9) ⇒ Single skin steel, unsure about corrosion protection (9) ⇒ Unknown tank construction (9)

Originally HARRIS presented a tank construction type of 'steel with GRP jacket', it was pointed out during the verification process that the type of tank that is 'steel with a GRP jacket' is in fact a polyurethane jacket.

Tank age could vary from new to several decades old. A site that has been recently re-developed may have had new tanks installed but unless there are site records that state a tank's age it will often be unknown, so the user is first asked if they know what the approximate tank age is. If they answer 'no' or 'unsure' a score of 7 is allocated. If an age is known, a further question is asked, >30 years old, score 8.8, 20-30 years old, score 7 and <20 years old, score 5.2. Not knowing tank age and unsure answers are scored on a range of 5.2 to 8.8, this gives a mid-point score of 7 (which is not the worst case scenario).

As tanks can be constructed of different materials, be double skinned or corrosion protected, so can the associated pipework system. Table 9.5 shows relative scores for this aspect of the storage hazard. These scores are generally higher than tank equivalents as pipes leak more than tanks do (Chapter 3, section 3.3.1). The following scoring scale is generated for pipework systems:

Non-metallic, secondary containment (7.2) ⇒ Non-metallic, no secondary containment (10) ⇒ Non-metallic, unsure about secondary containment (10) ⇒ Metallic, secondary containment, has corrosion protection (13.2) ⇒ Metallic, no secondary containment, has corrosion protection (16) ⇒ Metallic, unsure about secondary containment, has corrosion protection (16) ⇒ Metallic, secondary containment, unsure about corrosion protection (16.4) ⇒ Metallic, secondary containment, no corrosion protection (16.4) ⇒ Metallic, no secondary containment, no corrosion protection (19.2) ⇒ Metallic, unsure about secondary containment, unsure about corrosion protection (19.2) ⇒ Unknown pipework construction (19.2)

**Table 9.5:** Pipework construction and associated protective measures - with HARRIS scores

Pipework Construction	Risk No. for Type of Pipework	Risk No. for Secondary Containment	Risk No. for Corrosion Protection	Total Risk No.
Unknown construction	6	5.6	7.6	19.2
Metallic, no secondary containment, no corrosion protection	6	5.6	7.6	19.2
Metallic, unsure about secondary containment or corrosion protection	6	5.6	7.6	19.2
Metallic, no secondary containment, corrosion protection	6	5.6	4.4	16
Metallic, unsure about secondary containment, has corrosion protection	6	5.6	4.4	16
Metallic, secondary containment, no corrosion protection	6	2.8	7.6	16.4
Metallic, secondary containment, unsure about corrosion protection	6	2.8	7.6	16.4
Metallic, secondary containment and corrosion protection	6	2.8	4.4	13.2
Non-metallic, no secondary containment	4.4	5.6	-	10
Non-metallic, unsure about secondary containment	4.4	5.6	-	10
Non-metallic, secondary containment	4.4	2.8	-	7.2

The user is then asked about the age of the pipework system. If known, scores are allocated as follows: > 30 years, score 7.4, 20-30 years, score 5.6 and < 20 years, score 4. If they do not know or are unsure, a score of 5.9 is allocated.

The issue of tank/pipework age was raised during the verification process as it was not clear within the explanation provided by HARRIS that it was the age of the oldest tank/pipework that should be used. Many sites have undergone redevelopment where some tanks or some of the pipework has been replaced but not all.

To ensure that integrity is maintained in the fuel distribution system at a site, the tank and pipework system should be tested on a regular basis. HARRIS scores as follows: no evidence of any tests in the last 10 years, score 8; evidence for testing every 6-10 years, score 6.4; every 2-5 years, score 4.8 and < 2 years, score 3.2. If the testing interval for the site is not known, it will be scored at a mid-point of 5.6. The original options given for the tank/pipework testing

regimes were felt not to be correct during the verification process and the above options of testing were suggested and incorporated into the HARRIS rulebase.

The final storage hazards question relates to leak detection systems (Chapter 3, section 3.3.1) scored as follows:

- Manual tank dipping 7
- Static leak detection 5.2
- Monitoring wells (only) 4.8
- Statistical leak detection 4
- Automatic wetstock reconciliation 3.4
- Interstitial monitoring - pipes/lines/tanks 3.4

The most common leak detection method in the UK is not known, so if the user is unsure which one is most commonly used at the site, the mid-point has a score of 5.2.

Currently HARRIS can only deal with one leak detection selection which could introduce an error as many sites will operate more than one system e.g., statistical leak detection and monitoring wells. This should be incorporated in a subsequent version of HARRIS.

### *Dispensing Hazards*

In the dispensing area the pumps and the pump islands are important. Pumps have been manufactured to different standards, depending upon age. The most modern standard - BS 7117 - scores 3.2. An older standard is SFA 3002 and scores 4.8 (as does any non-BS 7117 pump). If pumps show no standard (they should all be fitted with a plate showing the required information) or the information is not known - this has been scored 6.2. In the UK most pumps will be of BS 7117 standard, especially where any redevelopment has taken place.

If the user does not know what standard of pump is used at the site being assessed, HARRIS directs them to check the plate displayed on the pump or to consider the overall age of the site. An old un-modernised site is scored as 4.8 and a modern site as 3.2. It is unlikely that non-standard pumps are being used at retail sites.

Where the pump islands join the forecourt creates an ideal location for any spills to escape the site drainage system. This junction should be sealed and the seal in good condition, this will score 3, if it is in poor condition, then it scores 6.2. An uncertain answer will score 6.2 as this joint (according to those experts consulted) is often in a poor condition.

Fuel can be delivered to the customer via the pipework system in one of two ways: by a suction or a pressurised system. In the UK most systems use suction (scores 5.4, pressure system scores 6.8). A pressure system is considered to be 'worse' as if a leak develops, fuel can still be pumped from the tank and the leak may go undetected for longer. As most delivery systems in the UK are of the suction/siphon type, the score for unsure is 5.4.

It was confirmed during the verification process that the majority of sites in the UK use a suction fuel delivery system. It was indicated that possibly one company (Mobil) uses a pressurised system.

### *Site Control Procedures*

The final section of the source characterisation concentrates on any site control procedures that may be present. One of the first items to check is for the presence of an interceptor and whether it is adequate for the site (HARRIS will give guidance if the user is unsure what would be adequate) as follows:

- None present                    9.4
- Present, not adequate       8.2
- Present, adequate            4.2

Again the unsure answer has not been scored as a worst case scenario of 'no interceptor' but at a mid-point of 6.8.

Even if an interceptor is present at the site the actual drainage system may not always drain to sewer. If the system drains to surface water, it scores 10, to soakaway, 8.2 and to sewer, 5.2. The distribution of these types of drainage systems is not known with any certainty for the UK, so an unsure answer has been scored at a mid-point of 7.6.

The ability to be able to isolate the drainage system in the event of a spillage during fuel dispensing (or delivery) may prevent free product leaving the site. If a drainage system can be isolated automatically, it will score 4 and if not, 8.4. If the user is unsure about whether the drainage system can be isolated or not, it is most likely that it can not (according to expert experience), so scores 8.4.

To ensure effectiveness the drainage system should be regularly tested. If there is no evidence of testing in the last ten years, score 7.6, tested every six to ten years, score 6.2, every two to five years, score 5.2, every two years or more, score 3.4. An unsure answer has been scored at the mid-point of 5.

During the verification process it was felt by the experts that the section on site interceptors needed to be clearer. A site may have an interceptor present but it may not be adequate or suitable for that site. Agency guidance recommends that any site interceptor should be capable of accommodating more than the volume of the largest tank compartment on site (Environment Agency, 1996d; Environment Agency, 1996e). There may also be two separate drainage systems on a site; one that takes relatively clean water from roof run-off etc. and a second that takes potentially polluted effluent from the site forecourt. One could discharge to surface water whilst the other could discharge to foul sewer. HARRIS could be adapted to take this into account.

This concludes the source characterisation phase of HARRIS and it now moves on to characterisation of the pathway and target terms. In terms of the usual decision-making route of the principal expert (and others) the target term is characterised first. If there is no target identified then any pathways do not need such detailed investigation. However, as HARRIS is a prioritisation tool, it will still evaluate the pathway term after the target term to carry out a full site assessment.

#### *Stage 4 - Target and Pathway Characterisation*

- Target Characterisation

HARRIS begins by checking whether there have been any incidents such as spills or leaks at the site in the past. If there has been an incident the user is asked to supply information on what was released, how much was released and whether any targets such as, for example, a surface water body was affected. However, if no information about a previous leak or spill is available, the situation is not treated as 'no leak' and the principal expert suggested that this scenario should score 5, as an 'unsure' answer. Table 9.6 shows these scores.

**Table 9.6:** History of previous releases from a site - with relevant HARRIS scores

Parameter	Product Type			
	Petroleum	Diesel	Other (e.g. oil)	Unknown
Product Risk Number	12.2	11.6	8.6	12.2
Volume of release > 10,000 litres	13.8	13.8	13.8	13.8
<i>Total Risk Number</i>	26	25.4	22.4	26
Volume of release 5-10,000 litres	10.6	10.6	10.6	10.6
<i>Total Risk Number</i>	22.8	22.2	19.2	22.8
Volume of release < 5,000 litres	7.4	7.4	7.4	7.4
<i>Total Risk Number</i>	19.6	19	16	19.6
Volume of release Unknown	7.4	7.4	7.4	7.4
<i>Total Risk Number</i>	19.6	19	16	19.6

There are several assumptions made at this stage. If an unknown product was released, a worst case of petroleum is assumed which scores 12.2. If a release volume is unknown it is assumed to be < 5,000 litres and scores 7.4. The majority of incidents at retail sites according to the



principal expert are < 5,000 litres, especially if there is no record of them. This information was verified by the other experts. Without a central database of release information or even a register of underground tanks the opinion is difficult to disagree with.

In terms of the volume of any previous leak/spill, it was felt that the original choices of <10,000 litres or > 10,000 litres were not representative of the majority of incidents which were usually considered to be less than 5000 litres. Consequently, options of <5000 litres, 5-10,000 litres and >10,000 litres were added to the HARRIS rule-base. If the volume was not known by a user HARRIS defaults to the scenario of <5,000 litres, as most incidents were thought to result in the release of less than 5000 litres of fuel. It was also felt that just because there were no incidents recorded on file for a site it should not be assumed that no release had occurred.

The following scale can be generated:

No release recorded or unsure about release (5) ⇒ Other product < 5,000 litres (16) ⇒ Other product of unknown volume (16) ⇒ Diesel < 5,000 litres (19) ⇒ Diesel of unknown volume (19) ⇒ Other product 5,000 to 10,000 litres (19.2) ⇒ Petroleum < 5,000 litres (19.6) ⇒ Petroleum of unknown volume (19.6) ⇒ Unknown product < 5,000 litres (19.6) ⇒ Unknown product of unknown volume (19.6) ⇒ Diesel 5,000 to 10,000 litres (22.2) ⇒ Other product >10,000 litres (22.4) ⇒ Petroleum 5,000 to 10,000 litres (22.8) ⇒ Unknown product 5,000 to 10,000 litres (22.8) ⇒ Diesel > 10,000 litres (25.4) ⇒ Petroleum > 10,000 litres (26) ⇒ Unknown product >10,000 litres (26)

The user is asked whether they have definite knowledge that the site had affected a target in a previous incident, and if so, what type of target it was. The scores are shown in Table 9.7.

**Table 9.7:** HARRIS scores where a target has been affected previously by the site under investigation

Target Type	Risk No. for Target Type	Target Definitely Affected in Past	Total Risk No.
Drinking water abstraction	14.6	15	29.6
Agricultural abstraction	11.4	15	26.4
Industrial abstraction	11.4	15	26.4
SSSI, nature reserve	10.4	15	25.4
Surface water body	10.4	15	25.4
Groundwater itself	10	15	25
Unsure	14.6	15	29.6

In the case where a user knows that a target has been affected previously but is unsure as to the type of target that was affected, the answer is scored as a worst case scenario of 29.6. HARRIS then moves on to what targets can be identified in the present and where they are located. These scores are shown in Table 9.8.

This gives a scale of:

Groundwater alone, unsaturated zone > 51m (10) ⇒ Surface water body 1.01-10 km away (15.8) ⇒ Groundwater alone, unsaturated zone > 26-50m (16) ⇒ SSSI/Nature reserve 200m-2km away (16.2) ⇒ Groundwater alone, unsaturated zone > 11-25m (17.2) ⇒ Surface water body 501m-1km away (17.8) ⇒ Agricultural/Industrial abstraction 200m-2km away (18.2) ⇒ Groundwater alone, unsaturated zone < 10m (19.3) ⇒ Surface water, 50-500m away (19.8) ⇒ Drinking water abstraction 5.01-10km away (20.6) ⇒

SSSI/Nature reserve, < 200m away (20.8) ⇒ Drinking water abstraction, 2.01-5km away (22.2) ⇒ Agricultural/Industrial abstraction, < 200m away (22.8) ⇒ Surface water body, < 50m away (22.8) ⇒ Drinking water abstraction, 200m-2km (25.6) ⇒ Drinking water abstraction, < 200m away (28.6)

**Table 9.8:** Current target type and location - with respective HARRIS scores

Target Type Affected Now	Risk No. for Target Type	Distance Away (m)	Risk No. for Distance	Total Risk No.
Drinking water abstraction	14.6	< 200 m	14	28.6
Drinking water abstraction	14.6	200 m- 2 km	11	25.6
Drinking water abstraction	14.6	2.01 km - 5 km	7.6	22.2
Drinking water abstraction	14.6	5.01 km - 10 km	6	20.6
Agricultural abstraction	11.4	< 200 m	11.4	22.8
Agricultural abstraction	11.4	200 m - 2 km	6.8	18.2
Industrial abstraction	11.4	< 200 m	11.4	22.8
Industrial abstraction	11.4	200 m - 2 km	6.8	18.2
SSSI, nature reserve	10.4	< 200 m	10.4	20.8
SSSI, nature reserve	10.4	200 m - 2 km	5.8	16.2
Surface water body	10.4	< 50 m	12.4	22.8
Surface water body	10.4	50 m -500 m	9.4	19.8
Surface water body	10.4	501 m - 1 km	7.4	17.8
Surface water body	10.4	1.01 km - 10 km	5.4	15.8
Groundwater	10	depth of unsaturated zone < 10 m	9.3	19.3
Groundwater	10	11-25 m	7.2	17.2
Groundwater	10	26-50 m	6	16
Groundwater	10	> 51 m	0	10

If the user is unsure about which type of target may be currently affected by the site, this is scored at a worst-case scenario of 14.6 for target type and a score of 14 for distance to the target making a total of 28.6.

The original list of target options was felt to be limited with one important omission that of groundwater as a resource in its own right. Other types of target suggested by the experts as additions for a later date, included surface water bodies important as fisheries and surface water bodies important in terms of amenity value. It might be expected however, as SSSI's are rated low as targets by a groundwater regulator, surface water bodies as fisheries may also be rated low.

The most important comment received during the verification process on this section of HARRIS was that the user needs to be able to select more than one target type: e.g. drinking water abstraction point and surface water body. Currently HARRIS can only accept one type of target and this would clearly need to be amended for a working system. However, the user is asked if a target has been affected in the past and this may be different from a 'current' target. For example, a site may be known to have affected a nearby surface water body in the past (incident recorded on file) but when assessing the site currently, a drinking water abstraction point may also be identified near to the site. The user is advised to choose the target type that they feel would be most vulnerable e.g., drinking water abstraction point followed by

agricultural abstraction etc. The HARRIS knowledge-base should be adapted to allow more than one current potential target to be selected.

- Pathway Characterisation

If the site could affect a drinking water abstraction point the first question HARRIS asks relates to Source Protection Zones (Chapter 4, section 4.2.3). To-date these zones have only been defined for drinking water abstraction points. If the site under investigation is situated in Zone I, this situation is scored 12, in Zone II, 9.8 and Zone III, 7.8. If no zone has been designated it is scored at a mid-point of 9.9 as there is a possibility that it will be zoned in the future but the likelihood as to which zone it may fall in is unknown. It is not known whether it is more likely to fall in Zone I, a worst-case scenario, or Zone III a best-case scenario.

The user is asked to identify what generic type of strata underlies the site. If it is mainly clay, this scores 5, mainly sandstone, 8.6 or mainly chalk, 9.8. If the strata type is unknown the worst case scenario of chalk is not assumed and a mid-point of 7.4 is scored.

The user is then questioned about groundwater flow (fissure or intergranular flow) and depth of the unsaturated zone. The scores HARRIS assigns are shown in Table 9.9. If the user answers unsure to one of these questions, the score is set at 19.1. Originally sections on depth to the water table and depth of the unsaturated zone were included in the evaluation version of HARRIS. The depth to the water table section was removed. Originally, depths of >51m of unsaturated zone scored zero for fissure and intergranular flow. This was felt not to be appropriate if the groundwater flow was mainly fissure flow and was adjusted accordingly.

**Table 9.9:** Groundwater flow and depth of the unsaturated zone - with respective HARRIS scores

Depth of Unsaturated Zone (m)	Risk No. Fissure Flow	Risk No. Intergranular Flow	Total Risk No. for Fissure Flow	Total Risk No. for Intergranular Flow
< 10	9.3	9.8	19.1	17.7
11-25	7.2	8.6	15.8	14.8
26-50	6	8.4	14.4	13.2
> 51	0	8.4	8.4	0

Permeability of the aquifer is assessed at this stage as high, score 10.4, medium, score 7.6 or low, score 5.6. An 'unsure' answer will default to the worst case scenario of 10.4. It was felt during the verification process that if the user was unsure as to the permeability the system should default to 'high permeability', this suggestion was incorporated into the HARRIS rule-base. The same comment was made about permeability of the unsaturated zone.

The concept of permeability is explained to the user if required and the next parameter introduces the concept of hydraulic conductivity in terms of the unsaturated zone. For sands/gravels with a hydraulic conductivity of  $> 10^{-4}$  cm/sec the score is 10.4, for sandstones,  $10^{-4}$  to  $10^{-6}$  cm/sec, 8.4 and clays  $< 10^{-6}$  cm/sec, 6.2. If the user is unsure, a value of 10.4 will be attributed as a default to sands/gravels, as the worst case scenario. The worst case scenario has been used for these two parameters rather than a 'mid-point' score as the principal expert considered these parameters as important. For example, a highly permeable aquifer could be vulnerable to a small spill/leak from a site, whereas a similar sized release from a site where aquifer permeability is low would not be at such a high risk. The worst case scenario is used as a default to 'err on the side of caution'.

Users are also asked to provide information as to the type of aquifer that is present below the site and related groundwater vulnerability information. Aquifer type was considered an important parameter by the experts and it was suggested that the user be presented with 'named' aquifer options such as 'Sandstones e.g. Sherwood Sandstone' or Millstone Grit'. This suggestion was incorporated, the information being taken from the Policy and Practice for Groundwater Protection (Environment Agency, 1998). A list of options for type of aquifers is shown to the user or the groundwater vulnerability maps can be used to identify the site location and hence aquifer designation. Options available are shown below:

- |   |      |
|---|------|
| • Chalk                                   | 10.8 |
| • Sandstones e.g., Sherwood Sandstone     | 10.8 |
| • Limestones e.g. Carboniferous Limestone | 10.8 |
| • Greensands e.g. Upper Greensand         | 10.8 |
| • Alluvium                                | 8.2  |
| • Sand/gravels                            | 8.2  |
| • Coal measures                           | 8.2  |
| • Millstone Grit                          | 8.2  |
| • Clays e.g. Jurassic clays               | 4.8  |
| • Mudstones e.g. Mercia Mudstone Group    | 4.8  |
| • Marls e.g. Permian Marls                | 4.8  |
| • Known major aquifer                     | 10.8 |
| • Known minor aquifer                     | 8.2  |
| • Known non-aquifer                       | 4.8  |

If the user is unsure at this stage, HARRIS directs them to the groundwater vulnerability maps but if they are still unsure a score of 10.8 (worst case scenario of a major aquifer) is assumed. The most frequently occurring major aquifer in England and Wales is the Chalk (Sir William Halcrow and Partners Ltd, 1988).

There are several parameters not currently included in HARRIS such as rainfall, soil type, presence of tunnels/services, or dilution factors, which could be incorporated at a later date if necessary and if deemed significant by further system evaluation.

### *Stage 5 - Prediction of the Consequences*

This may be described as the effect or potential effect of a pollutant release on an identified target (measured in terms of likelihood and magnitude) e.g., a petroleum release and the effect it may have on a nearby agricultural groundwater abstraction point. Prediction of the consequences may also be described as the 'chances' of the target being impacted by a release, i.e. the probability. The magnitude of any potential impact may be important in policy or risk acceptability terms.

In terms of groundwater pollution the magnitude of any incident could be described in terms of spatial scale (size and extent of plume) or the exceedence of regulatory standards e.g., drinking water quality standards. It could also be described in terms of financial effects such as the financial penalties incurred to a polluter if a drinking water abstraction point has to be closed down due to pollution. HARRIS focuses on what is the likelihood of a sensitive target being affected and whether one has been affected in the past. The magnitude of the impact is not investigated specifically as HARRIS is a prioritisation tool, the potential for any impact on a sensitive target is being measured.

It is at this stage that HARRIS uses the various 'risk numbers' allocated during the source, pathway and target characterisation stages to calculate a final risk number for the site. The final risk number is then equated to the Agency severity classification for point-sources of groundwater pollution (de Hénaut *et al.*, 1997) in terms of 'significance to groundwater' :

- High significance (risk number 296-350)
- Medium-High significance (risk number 251-295)
- Medium significance (risk number 207-250)
- Medium-Low significance (risk number 162-206)
- Low significance (risk number < 161)

The user is given the 'total risk number' for the site under investigation and states which significance category the site has been categorised in to. Each significance category is assumed to be of an equal size for the purpose of a HARRIS prioritisation (this need not be so). The range between best-case and worst-case scenario (Appendix C.2) has been divided by five to give the intervals shown. The user does not have to utilise the significance categories as each site is given an overall site risk number. Categorisation would be useful, however, when

considering a large number of sites in order that resources could be focused appropriately on those presenting the highest risk.

It was suggested during the verification process that the final risk number presented to the user (and the associated point-source classification) would be more usefully broken down into the score for source characterisation, pathway characterisation and target characterisation. These scores could be shown with 'total potential scores' for comparison. This would enable the user to understand the relative importance of the source, pathway or target element and of the site risk compared to a maximum score. This would be a useful area of improvement for any subsequent versions of HARRIS.

### *Stage 6 - Risk Calculations and Stage 7 - Risk Acceptability*

This stage of decision-making where the risk of a site to groundwater has been described (in this case semi-quantitatively) is often a policy decision. For example, the Environment Agency will not recommend to a local planning authority, approval for any new retail petrol-filling stations in a designated groundwater protection zone I (Environment Agency, 1996b). Tesco has been refused permission to build a petrol-filling station because of a potential threat to nearby groundwater supplies (Anon, 1995c). This is a policy decision based on risk acceptability. HARRIS does not assess risk acceptability but prioritises sites in terms of risk to groundwater and places them in a 'significance to groundwater' severity category which then allows policy decisions to be made. This prioritisation is accomplished on the basis of a hazard identification and assessment process at a site (source characterisation) an assessment of potential targets and possible exposure pathways (target and pathway characterisation) leading on to an assessment of possible consequences (based on pollutant behaviour). The outcome at this point is the categorisation of sites based on risk to groundwater, HARRIS does not indicate to the user whether sites in the high significance category should be closed down for example. A policy decision could be made to inspect all high severity sites once every four months and action taken to reduce the risk from those sites wherever possible. HARRIS could be expanded to include these kind of risk acceptability judgements and adapted as policy changes. Currently the system goes on to suggest some possible risk management actions if the risk to groundwater from a particular site is unacceptable.

### *Stage 8 - Risk Management Actions and Outcomes*

If a risk is found not to be acceptable then action is required. Using the example stated above, all high significance sites must be inspected at a regular interval, say every four months, and action is required to reduce the risk. Possible risk management actions need to be described as potential outcomes. This type of risk management information is included at the end of the assessment procedure and is currently for guidance only.

Guidance is given on what could be done to change (i.e. reduce) the risk rating. This advice would depend on whether the user was carrying out an *ex-post* or *ex-ante* assessment. However, the most obvious area for action in terms of a whole site assessment and potential risk to groundwater, is the source term. If a site is already active, pathway and target terms may be difficult to modify. HARRIS's question strategies will give the user an indication of what could be important at a site and areas where action could be possible. Currently, this last section gives some recommendations for action depending on the site category. For example, if the user indicated that the fuel delivery and dispensing area was in a poor condition and that there was no interceptor at the site, then site integrity and drainage issues could be addressed with the site operator.

What is crucial to the use of such a prioritisation tool, is the identification of the factors that allow for as full as possible a site characterisation. Figure 9.8 illustrates a flow-chart of the decision-making process when looking at an assessment of a site where no actual leak/spill has occurred and the site is being assessed for its potential to pollute groundwater. The information requirements of HARRIS are shown in Appendix C.1. The outline risk management process was also presented in Table 9.1.

#### *Reasoning With Uncertainty and Probability*

This is an important issue when dealing with risk-based decision-making especially in the environmental field. It is very rare to have all or even some of the information required to make absolute decisions. Expert decision makers become adept at making decisions with partial information and are able to reason with uncertainty using probability. However, these probabilities are usually expressed in a semi-quantitative or qualitative way rather than absolute numbers.

Within ESTA uncertainty factors can be used as part of the reasoning process, as can probability. Reasoning with probability can be used to associate a certain weight to each factor that has been investigated (parameter values). The weighting of factors can be determined by the expert, although it is usually determined by examining the statistical frequency of an event. The following example (in ESTA syntax) describes a parameter that evaluates whether a site is in a 'high severity category for point-sources'. The site would be considered in the high severity category for point-sources if the probability was  $> 0.8$ .

```
parameter high: 'high point source severity'  
type Boolean  
rules true if probability > 0.8
```

Probability is estimated by assessing, for example, the type of aquifer below the site, speed of groundwater flow, strata type and age of the tanks at the site. In ESTA syntax this could be represented as follows:

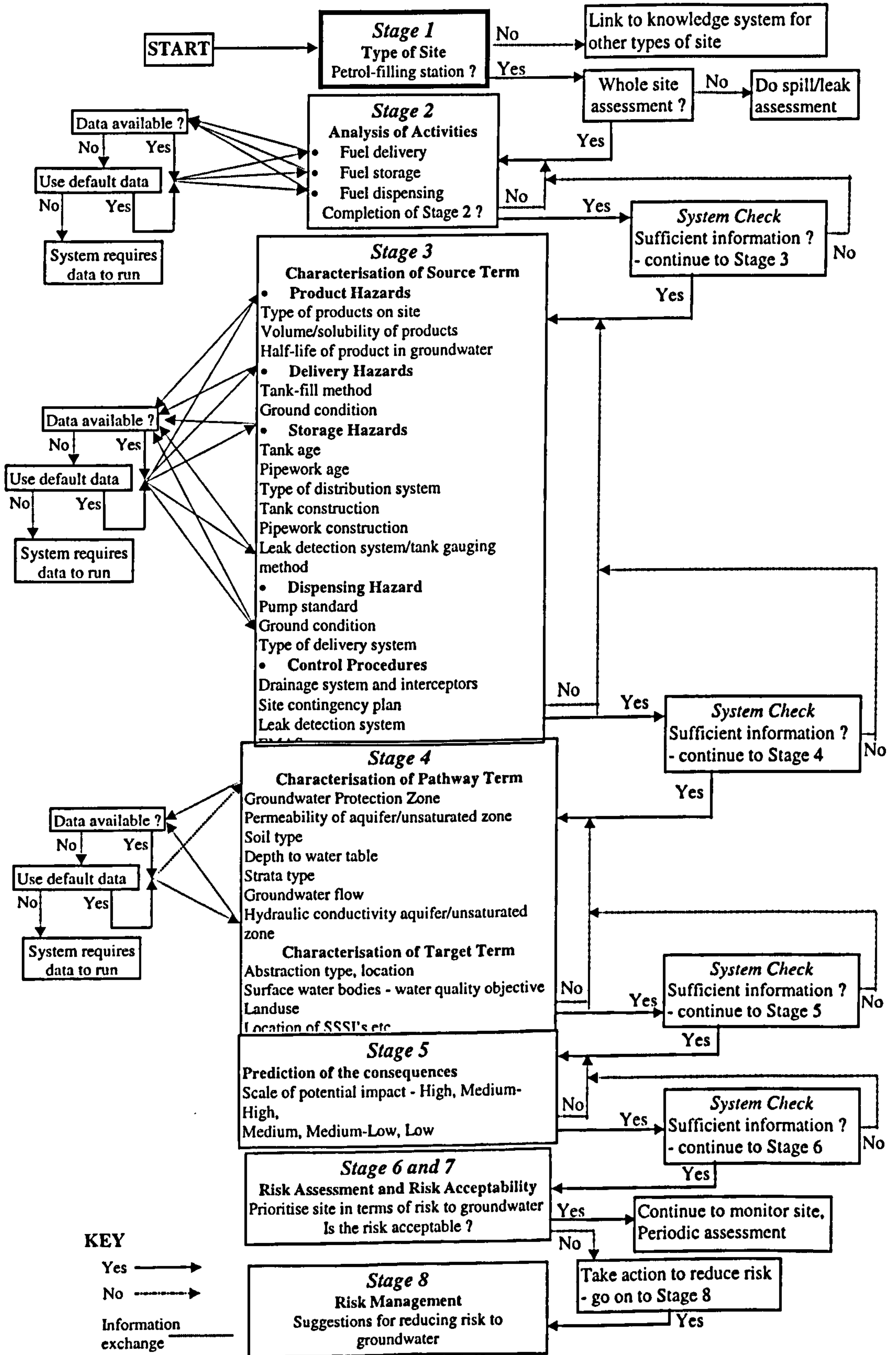


Figure 9.8: The full assessment process of HARRIS



parameter probability: 'probability'

type number

rules

1 if parameter aquifer\_type and groundwater\_flow and strata and tank\_age,  
0.8 if parameter aquifer\_type and groundwater\_flow and strata,  
etc.

Unfortunately this is a hypothetical example, data of sufficient quantity and quality are not available to make these kinds of probability judgements for use in HARRIS (a considerable amount of further research would be required). Experts rarely 'think' in terms of probability, therefore the knowledge acquisition process does not elicit a series of probability judgements. In the field of point-source groundwater pollution, statistical determination is not possible in a meaningful way, as there are a large number of variables and problems arise with obtaining a representative sample. The Environment Agency has only recently carried out a preliminary survey of the point-sources of groundwater pollution in England and Wales (de Hénaut *et al.*, 1997).

However, instead of using Boolean parameters, a knowledge system developed with the ESTA shell could use number parameters in the range -1.0 to 1.0. (i.e. fuzzy parameters) (Prolog Development Center, 1993: p64).

-1.0 .. -0.2 FALSE

-0.2 .. 0.2 UNKNOWN

0.2 .. 1.0 TRUE

To combine certain values in ESTA, the normal Boolean operators of AND, OR, NOT, can be replaced by numerical functions. By expanding the HARRIS knowledge base, the statement that 'the probability that the site under investigation presents a high risk to groundwater (or other identified targets)' could be evaluated. However, there is a need to identify evidence to support this statement. The expert could be used to do this but an enormous amount of extra information would need to be elicited, the 'fuzzy' rules that drive decision-making are difficult to articulate for the expert and difficult to record for the researcher. A way forward could be to describe a small part of a problem scenario and fully characterise that in terms of probability, rather than tackling the whole problem area in one go.

Any knowledge system whatever the design objectives or eventual outcome must be evaluated before any further work is carried out. System evaluation must include verification and as presented in this chapter, verification has been an ongoing process throughout development. The objective of the verification process as part of the system evaluation procedure was to check that:

- the rules are correct, consistent and complete;
- the system does make decisions that the expert would agree with and that are appropriate to the situation;
- the system does 'do' things in a sensible order
- the system does not ask inappropriate questions;
- the explanation facility is sufficient to explain how and why a decision was made by the system, and
- there are problems suitable to test the system.

The outcome of the verification process undertaken by the principal expert and others was that these objectives were achieved in principle, with weaknesses having been identified and remedied where possible. It must be emphasised that HARRIS was developed as a research prototype system. To develop the system further to satisfy these objectives fully would require a more extensive evaluation and development process. This can take several years and large financial resources before a system is ready for commercial use (e.g. RAISON™, Crowe & Booty, 1995; NWRI Software, 1997).

#### **9.4 SYSTEM VALIDATION**

User evaluation where the system itself was validated was a more distinct process. The system was validated by six potential users who were typical of the type of user the system was originally designed for: i.e. regulatory officers who were non-expert risk assessors and not experienced hydrogeologists, for whom groundwater protection formed a relatively small part of their responsibilities. The validation procedure consisted of an actual session with HARRIS assessing a particular site (Chapter 7, section 7.3.2) followed by a questionnaire.

The information given to participants about the site they were asked to assess and a copy of the evaluation questionnaire is given in Appendix A.4. Users were asked to evaluate the system in four respects:

- System performance issues
- Information provision and interaction issues
- Physical issues
- Personal attitudes to the system

##### *System performance*

Users agreed that HARRIS allowed them to categorise the example site satisfactorily (average score 4.67, on the scale 1 to 5, 5 representing a 'yes' and 1 a 'no' answer). The use of HARRIS helped users understand the source-pathway-target approach to risk assessment (score 4.33) and

helped them become familiar with the layout and particular hazards such a site may present to groundwater (score 4.0). The majority of users agreed that the type of information that HARRIS utilises to categorise sites is similar to the information they would use to carry out the same task manually (score 4.67). HARRIS acts as a site prioritisation tool which was felt to be helpful in prioritising sites by most users (4.5). In addition it was thought such a system would be useful to non Environment Agency staff such as environmental consultants (score 4.4), environmental health officers (score 4.83) and a company environmental manager (score 4.8).

Users did not experience any difficulties in knowing 'what to do next' (score 1.17) and most did not require external help to use the system. Questions posed by HARRIS to the user were felt to be appropriate and there were no particularly difficult to understand aspects. Irritating aspects of the system included the lack of a 'back button' and the speed of the system (too slow).

The overall positive aspects of HARRIS included: ease and simplicity of use; relative speed of an assessment and lack of subjectivity that could be introduced by the user. Negative aspects were: possible over-simplification; removal of specialisation from experienced personnel (however, the system is not aimed at experienced groundwater specialists) and the limited nature of the input and output information. Suggestions for system modifications to improve accessibility and usefulness included: provision of a spell-checker; provision of a 'back button' and provision of an area where the user can add free text to an assessment.

#### *Information provision and interaction issues*

The user instructions for HARRIS were found to be useful (score 4.83) and explanations offered by HARRIS generally sufficient (score 4.67). The speed of the system was questioned by some users (score 3.33) and more graphical information was required (score 4.0) however, the general appearance of HARRIS was considered satisfactory (score 4.33). All users could understand the questions put to them by HARRIS and all except one user felt that HARRIS provided enough information to act as a learning tool for point-source groundwater pollution.

#### *Physical issues*

The current system of a mouse-operated program was preferable to a key-board operated program and all users felt they could follow the screen layout. There were no problems using the buttons, physically being able to select options or entering text/values. One user, however, did comment that they did not recognise 'm' as standing for 'metres' when asked to enter a target location.

#### *Personal attitudes to the system*

Users were asked to indicate their strength of agreement on a Likert scale of 1-5, with 5 representing 'strongly agree' and 1 'strongly disagree'. Users felt that HARRIS was easy to use

(score 4.5) and not awkward to use (score 1.5). It was also felt that the sections in HARRIS were well integrated (score 4.0) did not show too much inconsistency in the advice provided (score 2.25) and were not too complex (score 1.33). Users felt confident using HARRIS (score 4.33) and did not feel that they needed to learn many things before they could use the tool (score 1.5). Most users felt that they would not require the support of a groundwater specialist before using HARRIS (score 2.17) but users were not so clear whether most people (even those with no expertise in groundwater protection) would be able to learn how to use HARRIS quickly (score 3.67). Finally, users believed that they would be able to use HARRIS in their work environment if required (score 4.33).

The objective of the validation process as part of the system evaluation procedure was to check that:

- solving the problem does actually help the user;
- the systems' answers are presented in an understandable way and at the right level of detail;
- the system is fast enough for the user, and
- the user interface is easy to use.

The majority of these objectives were met, albeit not fully. In particular the speed of the system was not considered appropriate. This was due to the machines that the system was running on rather than the system itself (486 processor, 8MB RAM). To run at an optimum speed HARRIS should be used with a Pentium processor and 16MB RAM. This system validation process allowed strengths and weaknesses to be clearly identified. Overall, HARRIS was well-received and was felt to help the user, its most positive aspects being ease of use, simple to understand and relative speed of carrying out an assessment compared to a manual process.

## CHAPTER 10

### 10 DISCUSSION, CONCLUSIONS AND FURTHER WORK

#### 10.1 THE RISK CONCEPT AND DECISION-MAKING

This research has focused on point-sources of groundwater pollution such as petrol-filling stations, the risk such sites may pose to the groundwater environment and how those risks may be managed by using a knowledge system to support risk-based decision-making.

Risk and the way people perceive risk (not just environmental risk) has been investigated by many authors (e.g. Slovic, Fischhoff & Lichtenstein, 1980; Douglas & Wildavsky, 1982; Royal Society, 1992; Adams, 1995). The scientific, formal view of risk is that it must be measurable and objective, implying that subjective or perceived risk is not measurable and is therefore in some way not a 'real risk'. Within the formal 'risk sector' attention has been focused on 'risk to human health' and developed from the assessment of major accidents in the UK (HSE, 1989) and chronic health risks in the USA (Petts & Eduljee, 1994: p116). This led to the development of a scientific objective approach to risk which tended to separate out risk assessment from risk management (which was seen as a legal, political and administrative task) (Royal Society, 1992) and favoured a highly quantified approach to risk in general. There has been a realisation that the quantified route may have been applied too readily (e.g. Somers, 1995) and to manage a risk requires scientific, technical and social value judgements (Adams, 1995: p215). The HSE have acknowledged that risk assessment is a mixture of science and policy (HSE, 1996a) and a risk-based approach to environmental decision-making is now part of the legislative framework in England and Wales (e.g. the contaminated land regime, section 57 of the Environment Act 1995). The Environment Agency also include risk-based environmental decision-making as a specific objective in their environmental strategy document (Environment Agency, 1997a: p25). However, what is perceived to be a risk, what is managed and how it is managed within a regulatory body such as the Environment Agency is a complex process that includes social or cultural value judgements as well as the scientific and technical.

The cultural theory of risk, even though it is a theory and has been criticised (e.g. Sjöberg, 1997) provides a useful model when combined with the myths of nature (Thompson, Ellis & Wildavsky, 1990; Adams, 1995) to begin to understand how 'risk' is managed in the regulatory context of the Environment Agency.

The Environment Agency is made up of many individuals who all hold beliefs about the world which can have an impact on how they perceive risk (not necessarily just environmental risk), which risks are acceptable and which are not. The Environment Agency is a relatively new government body but was formed from predecessor bodies with a longer history (such as the waste regulation authorities). There has been an emphasis on reactive *regulation* rather than

the provision of proactive guidance to regulated industry. Like many large organisations the Agency is bureaucratic and hierarchical in nature. When combined with a remit of environmental regulation the Agency fits in well with the hierarchical myth of human nature: i.e. those with strong group boundaries, who try and anticipate events and balance long and short-term goals and use the law to provide equality (Schwarz & Thompson, 1990: p7 & p66).

This representation becomes stronger when the myths of nature are added i.e. hierarchists will tend to perceive nature as perverse/tolerant - nature can withstand the majority of events but can be vulnerable to a particularly bad event, management is required to prevent too many excesses but generally the system can manage itself (Schwarz & Thompson, 1990: p5; Adams, 1995: p33). The management of risks to groundwater by, for example, prioritising sites for action, fits into this representation and can use a knowledge system to support those decisions. The Environment Agency as a body is responsible for the protection of the environment - their 'vision' is "A better environment in England and Wales for present and future generations" (Environment Agency, 1996c). The Agency's rationale is to curb the excesses of industry (the individualists) and to try to accommodate some of the requests of the general public, actions groups etc. (the egalitarians) whilst also trying to maintain the environment for those who are not interested (the fatalists). This is reflected in many of their policies: for example, to "manage water resources to achieve the proper balance between the needs of the environment and those of abstractors and other water users" and to "set priorities and propose solutions that do not impose excessive costs on society". The Agency, however, is made up of people, who individually may not share the hierarchical world-view or the perverse/tolerant response of nature.

To some extent most people will exhibit facets of all the differing world-views and views of nature depending on the circumstances. A person may be egalitarian and protective of the environment if 'Nastywaste Co.' wishes to open a treatment centre in their village but more individualist when the company they work for has been fined £20,000 for polluting the local river and killing a 'few fish'. The cultural theory of risk is just a theory but provides a useful framework for understanding risk management in a regulatory environment like the Environment Agency. The quantification of risk as far as is possible would be the hierarchist approach to help reconcile the beliefs of the egalitarians and the individualists.

The management of groundwater protection and the pollution of groundwater by hydrocarbon point-sources such as petrol-filling stations can be used to illustrate the need for risk-based environmental decision-making in a regulatory environment, and the advantages that can be obtained when this is supported by a knowledge system.

Groundwater by its nature is vulnerable as it is underground and can not be seen. Although groundwater provides approximately 35% of our drinking water in England and Wales

(Department of the Environment, 1996a) surface water tends to attract public attention. It has been proposed that the ignorance of the public and industry in general about groundwater and the consequences of its pollution is a contributory factor to the legacy of such groundwater pollution (Harris & Skinner, 1992b). It has also been proposed that by making people aware and interested in groundwater pollution problems is the means to "redress the existing situation and to change the priorities of the politicians" (Custodio, 1992).

Petrol-filling stations are a familiar sight in the UK and are to be found in all areas of the country. There are approximately 15,000 operational and many more closed or redeveloped sites. The number of operational sites has fallen consistently since the 1970's but site throughput has been on a parallel increasing trend (e.g. IOP, 1996 and 1997a). Hydrocarbon groundwater pollution is an active problem area in UK (Clark, 1995; de Hénaut *et al.*, 1997) and elsewhere such as the USA, (e.g. USEPA, 1988; USEPA OSWER, 1996). The scope of the problem means that managing the risk posed by such a large number of sites is potentially both a complicated and expensive process.

The management of groundwater pollution in UK is linked to the contaminated land regime. There has been a general lack of a co-ordinated approach to policy development to manage contaminated land and groundwater protection. The formation of the Environment Agency has only recently brought the management of the environment as a whole together. Previously, management was carried out by a wide variety of bodies (NRA, WRA's etc.) with a lack of communication between those bodies and few direct policy links. Now that these bodies are combined there is a need to ensure that the systems used to manage groundwater protection etc. are common across all regions ensuring consistency in the approach to decision-making.

Underpinning much of the environmental legislation in the UK has been the issue of sustainability and the implementation of the Agenda 21 programme (United Nations, 1992). However, policy development and groundwater regulation development in the UK has been piecemeal. The Groundwater Directive (80/68/EEC) was developed in 1980 but compliance within England and Wales has been slow with several changes of policy position (e.g., Department of the Environment, 1982; Department of the Environment, 1990). Initial interpretation of the Directive was 'incorrect' and resulted in a compromise of the strict 'pollution prevention' aim of the Directive and UK policy was reformulated by the 1990 guidance. The Environment Agency (the NRA at that time) responded to the Groundwater Directive by developing the Policy and Practice for the Protection of Groundwater which promoted sustainable groundwater use and which has recently been updated (Environment Agency, 1998). However, this policy is still only guidance and has no statutory function. Agency staff may only recommend a certain course of action that is protective of the groundwater environment, in accordance with their policy. A company could be prosecuted under the Water Resources Act if they ignored any reasonable recommendations and polluting

matter did enter groundwater but this would not be 'pollution prevention'. The Agency is also able to object to a petrol-filling station being built within a SPZ I for example, but it is the Planning Authority who recommends whether planning permission be granted or not. Explicit and transparent management strategies and the basis for making risk-based decisions would help aid communication between the various regulatory bodies.

Although the old reactive approach to contaminated land management and groundwater protection in the UK is being replaced by a more risk-based, proactive approach, care must be taken to ensure that attention is focused on the most significant risk sources. Some sites that could be remediated (i.e. technically feasible) may not reduce human health or environmental risks significantly and therefore be wasteful of resources. In contrast, aquifer remediation is a technically difficult and financially expensive proposition (e.g. Lerner *et al.*, 1993) and industry may be accused of 'no action' or of using, for example, bioremediation as a no action solution. Research results could be used to support this. For example, work done by Freeze and McWhorter (1997) on DNAPL removal from soils indicated that the risk reduction was often low in the long-term but the authors did not imply that containment in the short-term was not an effective strategy - research can be manipulated to support 'risk-based' decisions. There may be a tendency when levels of uncertainty are high to adopt increasing quantification, to be more 'objective' and to 'prove' that the decision made in a risk-based way was correct. This can also be problematical as illustrated by an example from the nuclear industry. Scientists from industry and academia approved of a site proposed for shallow land burial of radioactive wastes, calculating that if plutonium were buried there it would take 24,000 years to migrate 0.5 inches. They also said that the probability of off-site migration was non-existent - unfortunately 10 years after the facility was opened plutonium was found two miles off-site (Hurst, 1998: p73). This example demonstrates that even a 'quantified risk' may not be understood fully with all the issues - social, political as well as technical - having been considered.

A strong regulatory regime is no guarantee of risk reduction. The USA has good regulatory controls in the area of groundwater pollution and leaking underground storage tanks with a LUST support program. However, this does not ensure that all identified high risk sites are receiving the correct attention. When the USEPA Office of Inspector General audited the LUST Program, 126 out of 249 high risk sites (those known to have contaminated drinking water supplies) investigated were found to have not been dealt with properly in terms of clean-up or enforcement (USEPA OIG, 1997). Even when sites had been prioritised it is essential to have sufficient management control to ensure that the recommended actions are carried out effectively.

The risk management process is complex and many tools have been developed to support such a process, from qualitative 'check lists' to fully quantified exposure and contaminant transport



models. These types of tool were discussed in Chapter 4 (section 4.4) and many are highly sophisticated computer-based models. The management of human health and environmental risks has culminated in the development of integrated models for estimating human exposure and environmental contaminant transport. Examples include HESP (Veerkamp & Berge, 1994), GEOTOX (McKone, 1991), RISC-HUMAN (Goldsborough, Smit & Boer, 1995), SoilRisk (Labieniec, Dzombak & Siegrist, 1996) and RBCA (ASTM, 1995). These models are sophisticated and require an experienced, well-trained user to enable meaningful results to be produced. This does not imply that less 'complex' more qualitative tools (e.g. CCME, 1992) require less expertise on the part of the user. The opposite may be true, the more deceptively simple a model is to use, the more likely it is to be mis-used.

The use of such tools present some problems in that they can be time consuming to use and learn how to use. The user must be aware of the underlying conceptual model that the tool is based on (Ashley, 1994) and in particular any assumptions that it uses (Kastenbergh & Yeh, 1993). This type of information is often not explicit and transparent to the inexperienced user. The issue of 'transparency' has been identified by previous authors (in relation to human exposure) as an important area for future development of risk assessment models (e.g. McKone, 1991). Transparency and an understanding of the underlying concepts is important for ensuring that results from such a tool are accurate and relevant, but also for justifying or explaining proposed decisions to a third party.

Decisions regarding human health or environmental protection need to be made in a consistent manner, to be transparent and to make effective use of resources (expertise, time as well as financial) by focusing on high risk sites. These are unavoidably complex decisions that require many years of experience and high levels of expertise. The use of knowledge systems to support these type of decisions allows those with less experience to still make those decisions in a risk-based and consistent way.

## **10.2 THE ROLE OF KNOWLEDGE SYSTEMS IN RISK-BASED DECISION-MAKING**

Knowledge systems (discussed in Chapter 5) are tools that can, for example, allow non-experts to solve difficult problems in the manner of an expert (Hayes-Roth, 1984a; Waterman, 1986: p6). Such systems differ from more conventional computer programs in that they can be more flexible and represent human-reasoning strategies in a more natural way (Hayes-Roth & Jacobstein, 1994). Using such a system will also have benefits such as increased speed of carrying out a task, reduced errors, reduced training time and increased retention of 'corporate' knowledge.

Knowledge systems have been built to solve many different kinds of problem from medicine to agriculture. Environmentally-based systems have a shorter history (from the mid 1980's) but are now found in a wide variety of fields (Geraghty, 1993; Warwick, Mumford & Norton, 1993). Crowe (1994) suggested that certain characteristics of groundwater pollution are conducive to a knowledge-based approach as such decisions often have to be made with sparse or incomplete data, knowledge from a wide variety of fields is required and problem solutions are subject to regulatory constraints.

The development of knowledge systems has been identified as a groundwater protection research area by several authors (e.g. Crowe, 1994; Merchant, 1994). Several systems have been developed (discussed in Chapter 5, section 5.3), including the Defense Priority Model (Hushon, 1989b), AERIS (Robins & Clark, 1993) and RAISON™ (Crowe & Booty, 1995). Most of these tools are not specifically restricted to groundwater and may be termed multi-media tools (i.e. air, soil and water).

The NRA also identified the potential for knowledge system application within areas such as the assessment of planning applications in relation to groundwater protection and in the management of water resources (Glen & Mason, 1992). A successful prototype system, W-RAISA (Water Resources Management Intelligent Assistant) was developed that supported decisions surrounding the issuing of an abstraction licence (Ahmad & Griffin, 1991). It was acknowledged that most resources were used up at the knowledge acquisition phase and that W-RAISA could have been expanded with further funding.

A key objective of this research was to identify the knowledge that is currently utilised by experts in the area of regulatory groundwater protection with a focus on point-source hydrocarbon pollution. The associated objective was the identification of the requirements for effective design and application of a knowledge system. An essential element of the latter was the generation of an initial 'problem' that could then be used during the knowledge acquisition process. That problem in summary is that, although risk assessment is now gaining acceptance in the regulatory field it is often not applied consistently or fully understood by all staff. The Environment Agency is responsible for the protection of groundwater in England and Wales and has recognised point-sources of hydrocarbon pollution such as petrol-filling stations as being a potentially significant problem (de Hénaut *et al.*, 1997). The Agency is limited by the resources available to it (e.g. time, financial and expertise) and the use of a knowledge system could support non-specialist regulatory personnel to prioritise risks and risk management activities (Butler & Petts, 1997).

An important part of this research has been to investigate whether knowledge system development for such a problem scenario would be possible, justified and appropriate (Waterman, 1986; Hushon, 1989a; Crowe & McClymont, 1992) (Chapter 5). The risk-based

prioritisation of petrol-filling stations is possible, the problem characteristics are relatively well understood and an expert was able to articulate them (Chapter 7, section 7.2). The problem does require expert judgement, interpretation and complex decision-making- a novice would not be able to carry out the same tasks without support (Chapter 5, section 5.1.2). The knowledge-based approach to site prioritisation supports consistent decision-making which is one of the Environment Agency's main aims (Environment Agency, 1997a). Such an approach can also be more user-focused than other types of approach (e.g. use of manual checklists).

Justification for knowledge system development can be supported by the fact that human expertise within the Environment Agency in this particular field is relatively rare and is needed in many locations across the country. The forthcoming legislative changes in the contaminated land regime (Department of the Environment, 1996b) will also place responsibility on local authority personnel, who may have little specialist knowledge and restricted access to someone with the relevant information.

The nature, complexity and scope of the problem can affect whether knowledge system development is appropriate. The nature of the problem must be such that heuristic knowledge is needed to solve it. This is clearly the case with 'risk' and risk management as there is always uncertainty in risk. As a field, regulatory groundwater protection requires several years of study and many years of experience to be termed an 'expert'. The scope of the problem (i.e. focusing on one type of point-source, petrol-filling stations) is manageable but still retains its practical application.

### **10.3 DEVELOPMENT OF THE KNOWLEDGE SYSTEM**

The identification and co-operation of a suitable expert together with potential system users and their requirements was important to this research. The importance of these stages in developing a knowledge system have been demonstrated (e.g. Welbank, 1983; O'Neill & Morris, 1989; Berry, 1994). A set of criteria was developed to identify such an expert (chapter 7, section 7.1.2): the 'principal expert' for this research. They acted as a 'key informant' (Le Compte & Preissle, 1993: p166) and the success of the research is largely due this person. Problems with the identification of an expert or retaining their co-operation can greatly reduce the chances of successful system development (Welbank, 1983). The principal expert was able to articulate his reasoning strategies. The availability of such an articulate expert can not be relied upon for this type of research and although an advantage, the overriding requirement is someone who is interested and willing to take part.

The above statement also holds for potential users to some extent. Users were selected using a set of criteria and the majority were from the Environment Agency (or its predecessor bodies). It is clear that no common background can be found in the participating potential users. There

is no 'typical' groundwater protection officer. Nearly all were educated to first degree level or beyond and groundwater protection was not their sole responsibility. The tasks they carried out were varied but did require technical expertise and decision-making skills (e.g. responding to pollution incidents). Many felt that they had learnt how to do their job whilst observing more experienced colleagues and this may be an area where inconsistencies are introduced. Different people will have different operational methods which will be passed on if there is no structured training programme and relevant technical support is not available.

Sources of information that users employed also varied but came down to what was available to an individual officer - if it was available (e.g. toxicology database) it was used. Many users felt that it was hard to make decisions with incomplete or poor quality information, hence also providing for inconsistency to be introduced in the absence of a decision-support system.

User requirements of a computer-based decision-support system were relatively clear in that it must be available, usable (easy to understand etc.) and actually help them with their tasks (system usefulness or utility). However, the Agency is still a fairly hierarchical, bureaucratic body and user requirements must fit in with overall management strategy and the structured nature of the Agency as an organisation.

There is a wide variety of knowledge acquisition techniques that have been applied to knowledge system development (e.g. Kidd, 1987; Neale, 1988; Neale & Morris, 1988; Shadbolt & Burton, 1995). No one technique is more suitable than another but many authors agree that at least one technique or a selection of techniques should be used as part of the acquisition process (e.g. Kidd, 1985; Shadbolt & Burton, 1995). Most of the techniques used have their origin in social science and psychology research and have been adapted for use in the knowledge system development area. There is little guidance as to which technique is most useful for eliciting each type of information. This research adopted a multi-method approach to optimise effectiveness: i.e. the reduction in uncertainty.

Repertory grid analysis has been put forward by Hart (1986) as a suitable place to start. It was used to identify potential sources of groundwater pollution and how the principal expert felt those different sources were related. It did provide an indication of how the principal expert felt personally about risks to groundwater in general and that risk to groundwater from petrol-filling stations was low. This however, is the consideration of an individual site and does not take account of the 'cumulative effect' of thousands of sites across the country. Although this technique did enable an overview of the problem area to be built up it is a 'contrived' technique and not natural to the expert and becomes difficult to analyse with more than ten elements.

A series of semi-structured interviews were carried out to gain an overview of the area of groundwater pollution and more specifically hydrocarbon groundwater pollution. Interviews

were used to achieve certain objectives such as identifying the types of information the expert uses, sources of information, how information was built up etc. (Chapter 8, section 8.2.2). Interviewing allows the gathering of background information and is familiar to the expert. However, there is a tendency to focus on atypical or rare events and it is easy to discuss matters that are not strictly relevant.

It became clear that the principal expert uses the Source-Pathway-Target model (Chapter 2, section 2.1.5) when assessing a groundwater problem but re-orders this to a Source-Target-Pathway model. This was found to be important especially when the prototype was developed and evaluated. The reasons why the target is considered second were not readily articulated. However, if the target does not exist or is of low importance then the implications of a pathway being present or not are unimportant. No pathway may mean no risk to target, but not necessarily. Targets are considered second possibly to assess how 'quickly' a situation must be dealt with. For example, if a source is likely to contaminate a drinking water abstraction within one week, immediate action is required. The expert considers several areas where information is needed, such as, what is the volume of the release, what has been released etc. It is clear that these are question 'areas' and information is built up as and when it becomes available, there is not necessarily a strict order for obtaining these pieces of information. It is this kind of knowledge that can be difficult for a non-expert to gain, i.e. the ability to move on to the next thing whilst making sure that all necessary information is obtained. In such a situation a knowledge-system is ideal as a decision-support tool.

The principal expert was a regulatory groundwater specialist and as such is perhaps understandably focused on groundwater as the target. This is apparent in the types of information needed by them when assessing the target. This limited regulatory focus also resulted in a lack of consideration of human health issues. This was not so much the case for other experts (e.g. academics) as demonstrated in the risk rating phase of knowledge acquisition (Chapter 8, section 8.2.5).

According to the principal expert, pathway information was often initially restricted to aquifer type and groundwater vulnerability information. Pathway information is often the hardest to obtain and has the highest degree of uncertainty. There are many tools available to model contaminant and groundwater flow (e.g. MODFLOW, Ashley, 1994) which require an experienced user to obtain meaningful results. It is possible to incorporate these types of model into a knowledge system (e.g. RAISON™, NWRI Software, 1997).

The knowledge acquisition technique of 'protocol analysis' (off-the-job) was used in conjunction with interviewing: i.e. the principal expert considered a case-study and then described verbally their problem-solving actions. It was used to identify the order of the decision-making process by utilising actual case studies where groundwater had been impacted

and was relatively successful at this, although difficult and time-consuming to carry out. Protocol analysis has been used successfully in knowledge system development by others (e.g. Ericsson & Simon, 1984). It does allow typical events to be used and is more natural for the expert. However, the expert can feel under pressure and might feel that their expertise is being questioned (not during this research). The results of the repertory grid analysis, protocol analysis and interviews were used to generate the flow-charts shown in Chapter 9 and eventually led to the development of the conceptual model described in Chapter 9. By producing a visual representation of the decision-making process by means of a series of flow-charts, the process becomes more explicit to both the expert and system developer, allowing easier and more effective modification (Price *et al.*, 1995).

Two other knowledge acquisition techniques - concept sorting and risk rating exercises were used to advance the conceptual model and support development of the prototype knowledge system. Concept sorting was used to investigate relationships between concepts specific to hydrocarbon groundwater pollution by utilising information gained from other methods such as interviewing. Concept sorting as a technique is relatively quick and can be used to generate rules directly but it is a contrived technique and requires some expertise to complete properly. Concept sorting results (Chapter 8, section 8.2.4) illustrated that there were differences amongst those who took part (i.e. regulators, academics and those from industry). It is acknowledged that the sample sizes were small but within acceptable limits for the technique (e.g. Dane, 1990).

Sorting concepts into source, pathway and target terms, perhaps not surprisingly gave the highest levels of agreement with the principal expert. These types of descriptors may be more easily categorised than terms such as high, medium or low risk. Sorting on the basis of risk to groundwater (Sort 2) and in terms of 'response time' (Sort 5) was in effect a similar process but agreement was lower for Sort 5. This may be due to a variety of reasons but could reflect the responsibilities of those who took part. If the participant was not used to making decisions about response times as part of their duties for example, you might expect less agreement with the principal expert. It may also be connected to the use of an emotive word such as 'risk' in Sort 2 but not Sort 5. There may also be genuine differences of opinion and this is an area that requires further research.

The levels of agreement with the principal expert were investigated further to try and identify the source of the disagreements. When considering source, pathway and target terms there was a high level of agreement but disagreement appeared to be introduced by the choice of what was considered an irrelevant term. This was not the case when categorising on the basis of risk to groundwater. Terms that were considered to be high risk or irrelevant gave higher levels of agreement. The reasons for this are not clear. It may be due to the words 'high risk' and

'irrelevant' in terms of risk to groundwater were more easily categorised than irrelevant in terms of source, pathway and target.

When participants were asked to sort terms on the basis of 'information requirements' a relatively low level of agreement with the principal expert was found. This is consistent with what would be expected as if there were high levels of agreement, participants would be performing as the expert was. Not surprisingly the highest levels of disagreement were over whether to pass something on to a specialist or not. The principal expert tended to only pass things on to a specialist consultancy for detailed study when there was not the luxury of time to study it within the regulatory environment.

When assessing whether something requires immediate action or not, levels of agreement were quite high. Disagreement arose when deciding if little or no further action was required, as the non-experts were not clear when something could be discarded or ignored and may be over-cautious. This may be a facet of 'expertise' and how we learn to carry out complex tasks - learning is not done in one chunk (e.g. Newell & Simon, 1972; Anderson, 1995).

Levels of disagreement were investigated further by studying the 'scale' of the differences. Figure 8.10 (Chapter 8) illustrates that, compared to the random distribution, all groups (regulators, academics, industry) performed at a higher rate i.e. the graph is skewed towards the lower levels of difference than the random distribution. The academic participants showed the greatest level of agreement with the principal expert and were used to describe a 'Measure of Expertise'. This is the difference in expert performance from what might be expected if the sorting process had been random. This is purely an arbitrary measure of expertise but does highlight that there are differences in performance. This is also an area that would benefit from further research.

The risk rating exercise also highlighted these differences. The risk-rating exercise was used to obtain specific ratings based on expert knowledge in an attempt to semi-quantify some of the relationships identified by concept sorting etc. A large number of concepts can be rated and a 'scale' can be applied to the results. However, there is a possibility of misinterpreting these scales. A considerable amount of expertise is required to carry out such a risk-rating exercise and it is only practicable with a small group of participants. The principal expert tended to rate source-based concepts in the medium and below categories (Chapter 8, section 8.2.5) with pathway and target concepts rated medium-high to high. When other participants were included, the distribution changes (Figure 8.14) most notably in that pathway concepts shift towards the medium category. The differences between academic, regulator etc. were investigated further to see if any patterns could be identified. Regulators were more likely to categorise source concepts in the low category than academic or industry participants. With pathway concepts, regulators were more likely to use the medium category but still at a lower

rate than other participants. With target concepts, all participants used the higher rating categories to some extent but the regulatory participants used the lower three categories i.e. medium and below, more often.

The principal expert's background as a regulator with less involvement in site management issues undoubtedly had a significant impact. An expert more focused on site management issues e.g. the different types of leak detection system available, tank construction etc. may be aware of such differences and the potential impact on groundwater, which could of given different results.

Those who took part in the risk rating exercise were the most skilled participants in this research and this may have enhanced any differences between regulators and academics for example. The regulator may have more experience of dealing with these types of problem on a practical level, while the academic may have greater theoretical skills and take a more cautious approach. Differences between experts and those with less or different experience is to be expected and has been found by other authors using similar knowledge acquisition techniques (e.g. Hoffman *et al.*, 1995). Further investigation would be warranted however.

The differences observed as part of this research could also be thought of in terms of the cultural theory of how people view risk (Douglas & Wildavsky, 1982; Thompson, Ellis & Wildavsky, 1990). The principal expert was a regulator and could therefore be termed as being part of a hierachist organisation (even if personally they may hold different world-views). Hierachists see the use of law as providing equity between the individualist (e.g. industry) and the egalitarians (e.g. environmental protection groups). By using the current groundwater protection legislation and policy framework of the Environment Agency (even though it may not focus on human health) human health will be protected. In terms of groundwater itself, a hierachist will see nature as able to take a certain amount of abuse but require protection from the worst excesses of industry. By enforcing the law and developing sustainable policies such as the groundwater protection policy, nature is protected too.

The results gained during the knowledge acquisition process and the requirements of effective knowledge system design and application were used to generate a conceptual model of the problem area (Chapter 9, section 9.2). A series of flow-charts were developed which formed the basis of the prototype knowledge system - HARRIS. The 'construction' of these flow-charts was an essential part of the model development and they were designed to retain a sense of the original process the expert undergoes when solving a similar problem (e.g. Clarke *et al.*, 1992). The development of a conceptual model allows the model to be presented to the developer and the expert in a more explicit and visual way. This enables refinements and identification of errors to be carried out more effectively. The conceptual model was built up in stages, typical



of the incremental method of prototyping and system development and is felt to be a more successful method of system development by some authors (e.g. Clarke *et al.*, 1992).

The knowledge acquisition phase of system development has traditionally been seen as the 'bottleneck' in the development process (Feigenbaum, 1983). This research has shown that it is indeed a difficult and time-consuming process. However, it is also clear that a well-planned acquisition phase based on a clear problem definition is critical to successful development. In addition, of fundamental importance is consideration of potential system users; who they are, what tasks they carry out and what their requirements are. This highlights the need for system evaluation to be included as part of the development process, where users can have an input.

The final outcome of the knowledge acquisition stage is the generation of a conceptual model which then lead on to the development of the computer prototype (Chapter 9, section 9.3).

#### **10.4 THE HARRIS MODEL**

The prototype knowledge system - HARRIS - that was developed, is based on the conceptual model that was the outcome of the knowledge acquisition process and is a representation of expert knowledge and judgement. The specific scores in HARRIS were obtained from the risk-rating exercise.

The example risk management process illustrated in Table 9.1 uses a petrol-filling station as an example. There is a likelihood of actually knowing some of the information required by HARRIS in a desk-based ranking situation compared with a site audit, for example. Much of the information required by HARRIS is more readily available on-site, for example, the site operator may be available for questioning and site documentation may be accessible. The numbers of 'unknown' answers can be kept to a minimum (reducing uncertainty). It is suggested to the user that a site visit is nearly always beneficial and if a site is categorised without one it should be re-categorised as soon as one is carried out.

There is an issue of potential levels of uncertainty and sensitivity of the ranking as opposed to knowledge/information availability, that needs consideration. Many of the default answers will categorise sites higher than 'needs be' i.e. be overly protective, although many are not set at the worst-case scenario based on expert judgement. The user can not change default scores and can not actually see any of the scores (in order to try and prevent the highest score being chosen when there is uncertainty).

HARRIS is based primarily on the principal expert's knowledge (although the system was verified by two other experts). Certain parameters were considered to be so important in terms of risk to groundwater that a 'worst-case scenario' should be used. Examples include when a

known impact has occurred but to an unknown target - a worst case scenario of a drinking water abstraction as target was considered to be appropriate. If uncertainty is encountered when assessing other types of parameter where a worst-case scenario was not considered by the principal expert to be appropriate, i.e. not critical decision points, a 'half-way' stage is used to score that parameter. The rationale provided by the principal expert for this was that, although a worst-case scenario may not be appropriate, it does not necessarily follow that a 'best-case' scenario may be either. In order to preserve an acceptable level of conservatism in areas where uncertainty was an issue, a 'half-way' point was considered to be most suitable.

By not resorting to the worst-case in all uncertain situations a more realistic situation will be described. The expert is using probability (based on experience) to decide that in the case of many parameters used to assess a site, the worst-case will not happen and nor will the best-case. This method was utilised by the Canadian CCME National Classification System for contaminated sites (CCME, 1992). Even if the 'wrong' decision may be made by using the worst-case, the knowledge system supports consistent decision-making. In addition it is possible for the user to analyse why such a decision was made and review the situation by using the system 'explanation facility' (the user is not able to go back to a previous section of HARRIS but this could be addressed in subsequent versions). It would not be practical to score all sites as high risk to groundwater based on lack of data. Sites must be prioritised and resources focused on those sites most likely to present a high risk. This is the basis for risk-based decision-making and has been utilised by the USEPA in their Underground Storage Tank program (USEPA, 1988) with the development of the RBCA standard for example (ASTM, 1995).

An assessment with HARRIS begins with the assignation of a 'base-risk number'. HARRIS only deals with petrol-filling stations currently but could be developed to take into account other types of point-source. A base risk number set at the start of the prioritisation process gives an indication to the user of where petrol-filling stations can be rated in relation to other point sources. The example point-sources identified by the principal expert during the construction of a repertory grid (Chapter 8 section 8.2.1) are a highly personal selection. In order to provide a more objective selection of point-sources a ranking process could be undertaken by a variety of groundwater specialists, maybe using a technique such as Delphi (Mostyn, 1985).

The source term is considered first in HARRIS, then target then pathway following the process of the principal expert. There may be an argument for assessing target first, as if no sensitive target can be identified then there is no need to go through hazard identification etc. but if there was uncertainty about a target it would still be necessary to complete a full HARRIS assessment. Target characterisation could be inserted after source information related to product type and volume. If a sensitive target is identified the system could return to delivery

hazards etc. This was in fact how HARRIS was originally presented but when evaluated by the principal expert and others, it was thought to be potentially confusing to an inexperienced user. It is agreed that there may be 'no point' carrying on through a detailed source characterisation if no sensitive targets can be identified in a strict interpretation of a risk-based approach. However, in terms of system usability, utility and user-centred design the source-target-pathway approach is considered more appropriate.

The choice of certain parameters and options provided by the principal expert for HARRIS can also be criticised, for example why is spill/leak volume set at > 10,000 litres? Wherever possible parameters and parameter options have been taken from the literature (e.g. Environment Agency, 1996b) and adapted in line with the principal expert's viewpoint. This of course does not mean they are not open to reinterpretation and if the development of HARRIS is continued and more experts are consulted, parameters and parameter options within HARRIS would almost certainly change.

The scoring process obtained from the risk-rating exercise etc. is necessarily a personal view of the problem area and some scores may even appear to others to be wrong. For example, pipework age scores slightly lower than tank age and it is usually assumed that pipework fails more than tanks. Age is a significant factor in corrosion of metal tanks/pipework therefore it may be assumed that pipework age should score higher than tank age. However, those who took part in the risk-rating exercise etc. may have been using a different set of assumptions. It has been stated for example, that pipework generally fails at a higher rate than tanks but usually at a younger age i.e. sooner after installation than tanks (e.g. Osgood & Swokel, 1986).

Another criticism of HARRIS is that the choice of target is limited. The user is directed to choose a drinking water abstraction as a priority compared to a surface water body. This was commented on by system users and expert evaluators, the user needs to be able to select as many targets as can be identified.

The inevitable weakness of basing a model on one expert (or a small selection of people) is that they may be wrong. Their opinions may be open to debate, as are all expert opinions. There is no such thing as the ultimate expert who has all the right answers, there will always be debate and a knowledge system such as HARRIS must be based on compromise. It is for this reason that the verification and validation processes are important. At the prototype development stage, it would not be feasible to use a panel of experts as compromise would be too difficult to achieve in the time scale available. If the system is progressed to a commercial footing however, it may be possible and the verification process would certainly be more extensive.

The validation process that was undertaken with HARRIS showed that the system was generally well-received (Chapter 9, section 9.4. The size of the validation sample would have

to increase if HARRIS was developed into a complete model, and there would also be a need to identify a number of potential users from each user group (industry etc.). Validation should be undertaken at several stages and not left to the end when a system is just about to be launched commercially, allowing a system to be constantly adapted and refined. System verification and validation are important processes to any system development (even a prototype) but become even more important if the system is to reach the commercial stage. These kind of processes can be used to provide for a quality assured system if carried out to a standard (Tepandi, 1997).

## 10.5 FURTHER WORK

Although the research objectives have been achieved there are several areas where improvements could be made and areas for further work have been identified as a result of this research.

A wide variety of tools were identified that support risk-based decision-making (both knowledge-based and more conventional systems). However, what is not frequently reported in the literature is how successful such systems were or if they were not successful, why they failed. Identification of the most utilised tools and a benchmarking exercise to compare them would give more information as to why certain tools are successful, for example, the use of a user-centred system design.

During the knowledge acquisition phase of system development it was noted that there were differences in performance between experts and between non-experts and experts. This was highlighted by the concept sorting and risk-rating exercises. Further work using these techniques with larger sample sizes may help characterise the differences between academic and regulator performance for example. Using experts from a wider variety of fields may also help to identify genuine differences of opinion. Experts and non-experts are known to carry out complex tasks differently and these differences could be investigated in the context of risk-based decision-making in relation to point-source hydrocarbon groundwater pollution.

There are also a wide variety of knowledge acquisition techniques available and the use of other types of technique may be advantageous. One technique in particular, the Delphi technique, has been used in risk-based research previously and could be used to expand on the results obtained from the risk-rating exercise used here.

There are a range of improvements that could be made to the prototype knowledge system. The use of a GIS module would allow any location related parameters within HARRIS to be determined more accurately. A GIS module would also make the system more visual and possibly more usable (this could also be tested). The types of site that HARRIS is suitable for could be extended as it is currently restricted to petrol-filling stations.

A sensitivity analysis that could further test and validate the prototype system would be advantageous. There would be a need to identify a range of real petrol-filling stations that have the potential to pollute groundwater (or may have actually polluted groundwater already) where the site has already been investigated and there is sufficient information to be able to use the prototype knowledge system satisfactorily. This was beyond the scope of this research but would provide a logical step forward for future research in this area.

A structured survey of the state of petrol-filling stations in the UK would provide valuable information. This would enable a database to be constructed focusing on petrol-filling stations as a source of hydrocarbon groundwater pollution. At the time of writing there is no central database that can be referred to by officers of the Environment Agency (or anyone else) that gives basic information such as numbers of sites, location, past site history, current site activities, current site construction etc. Some of this type of information is partially available from a variety of different sources - for example the Institute of Petroleum - and some Agency regions keep information databases on contaminated land, e.g. the Midlands Region. The Southern region does have a database of petrol filling stations but for that area only. Information is not held centrally and made available to all and therefore the knowledge and skills required to deal with actual or potentially polluting incidents is fragmented across the UK. This is of course not just associated with petrol-filling stations as sources of groundwater pollution but applies to pollution sources in general and contaminated land in particular in the UK.

Setting up some kind of database on a national scale will in the longer term allow more detailed information to be used in site assessments with a consequent reduction in uncertainty. Before 'hard data' can be collected, expert opinion and experience can be collected to provide information as to the 'wider picture'. As more information is collected and analysed certainty factors could be applied e.g., 40% of tanks will fail by the age of 15 years. This approach has been successfully adopted by the USEPA Office of Underground Storage Tanks in their UST Program. When underground fuel tanks were identified as being a significant source of groundwater pollution in the USA (in the early 80's) information was collated on what type of sites were causing a problem, whether it was leaking tanks or leaking pipes etc. This was done by using the knowledge already held by tank installers, site operators etc. Industry was fully involved in this process and remains so today (USEPA OSWER, 1987; PIRI, 1997). This kind of approach is rarely practised in the UK regulatory environment and perhaps the US model could provide some useful 'pointers' for the future of contaminated land management and even pollution control in general.

A long-term goal of such a knowledge-based approach to the problem of hydrocarbon groundwater pollution could be to incorporate this information into a much larger system which would have a wider application. This has been done within the Canadian regulatory

environment with the system called RAISON™ (Crowe & Booty, 1995) and also in Italy with the RISFA system (Cicioni *et al.*, 1994). These systems are in reality several systems that can be linked together providing great flexibility and access to a large amount of information. An important factor in these types of systems is the ability to integrate GIS information which makes the system visual and possibly more attractive to users.

## 10.6 CONCLUSIONS

In summary, a knowledge-based approach to support risk-based decision-making in the area of point-source hydrocarbon groundwater pollution is appropriate in the regulatory context of the Environment Agency. Expert knowledge is required to make those decisions and currently experts within the Agency are rare and their knowledge can be inaccessible to the 'ordinary' officer in the field. The use of a knowledge system enables that officer to incorporate the decision-making strategies used by the experts into their own decision-making processes, it enables that officer to gain that expert knowledge and enhances consistent decision-making within the Agency as a whole.

Development of a knowledge system as a support tool for risk management decisions associated with point-source hydrocarbon groundwater pollution is a valid and valuable approach to the problem. A prototype knowledge system - HARRIS Hydrocarbon and Risk Related Information System, has been developed. Such a system is more valuable than many other tools attempting to solve similar problems (e.g. paper-based ranking tools) for three main reasons

- (i) it is explicitly and transparently based on expert knowledge
- (ii) it has been formulated on the basis of an understanding of how the non-expert responds to risk issues; and
- (iii) it provides explicit and interactive help to the user

The identification and co-operation of a suitable expert for knowledge system development is essential. Although a set of criteria were used for this research to identify what is considered an expert (at least ten years of experience for example) co-operation and support for the research are more important to a successful outcome.

Knowledge acquisition techniques used when developing a system are not always reported in detail in the literature but often a limited number of techniques are used such as literature searching and interviewing (e.g. Moula, Toll & Vaptismas, 1995). Several acquisition techniques were used for this research: repertory grid analysis, protocol analysis, semi-structured interviewing, concept sorting and risk rating. The use of multiple techniques for this

research has improved the quality and effectiveness of the knowledge acquisition process but it is still a time-consuming and difficult process for all involved.

Although some knowledge acquisition techniques were more successful than others in the provision of information to feed into the conceptual and computer-based model development (e.g. concept sorting and risk rating as opposed to repertory grid analysis) all provided useful results. The method of developing a conceptual model which then supported development of the prototype system was successful, allowing changes and refinements to take place during the development process. It is this process of staged system development which is considered to provide a contribution to the advancement of the production of practical decision-support tools.

The identification of users and their needs was also found to be essential to successful system development. Users from within the Environment Agency are willing to accept new technology such as computer decision-support systems but have certain requirements such as having all necessary information in the system, so other sources of information do not have to be consulted as well. It is essential that with the development of tools such as knowledge systems that potential users must be carefully identified before development starts and those users must be involved in that development.

Further work on the differences in expert and non-expert performance in the context of risk-based decision-making in relation to point-sources of hydrocarbon groundwater pollution, would be beneficial. This could be linked to improvements in the prototype knowledge system such as the addition of a GIS module, and the development of a national 'database' of petrol-filling stations thus providing detailed information for site assessments. This would allow HARRIS to be further validated. However, a long-term goal of using a knowledge-based approach to the problem of hydrocarbon groundwater pollution would be to incorporate this information into a larger system with greater flexibility and access to a wide range of relevant information.

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## APPENDIX A

### USER EVALUATION PROCESS

#### A.1 Example of initial questionnaire given to potential system users at user analysis stage

##### PRELIMINARY QUESTIONNAIRE FOR POTENTIAL SYSTEM USERS

As part of some research being carried out at the Centre for Hazard and Risk Management at Loughborough University of Technology into groundwater pollution, I need to investigate the needs of people likely to use any system developed. I will be coming to talk to you in the near future about your job, what you do and how you do it but before then if you could complete the short questionnaire below it would be a great help. Anything you put down will be for my research purposes only and will be kept confidential. This questionnaire should take about 10 to 15 minutes to complete.

##### *General Information*

1. Your name ?.....
2. What district of the NRA do you work for ?.....
3. What is your official job title ?.....
4. What level/grade are you ?.....
5. Who do you report directly to ?.....
6. Are you responsible for anyone other than yourself ?                      YES/NO
7. How long have you worked for the NRA ?                      .....years .....months
8. Has this always been in the same post ?                      YES/NO
9. If you answered 'no' to question 8, what were your previous posts ?  
.....  
.....  
.....
10. What qualifications do you have beyond 'A' levels ?  
.....  
.....  
.....
11. Have you been on any training courses whilst working for the NRA ?    YES/NO
12. If you answered 'yes' to question 11, what were these training courses about and were they 'internal' or 'external' ?  
.....  
.....  
.....

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*Information Sources you use at Work*

13. When carrying out your job do you ever refer to external sources of information, such as legislation for example ? YES/NO
14. If you do use information other than what you carry round in your head, what sort do you use - tick the relevant line and add your own information sources
- Journals
  - Legislation (Acts, statutory instruments, circulars etc.)
  - NRA policy documents
  - Maps
  - Text books
  - Other(s).....

*Computer Use*

15. Do you use a computer at home or at work ? YES/NO
16. If you do use a computer, how frequently do you use it - please tick the relevant line
- less than once a month
  - a few times a month
  - a few times a week
  - once or twice a day
  - regularly throughout the day
17. What sort of things do you use the computer for - please tick the relevant line or add your own
- Word-processing
  - Graphics
  - Database use
  - Other(s).....

Thank you for taking part. Please bring this questionnaire along with you when I come to talk to you.

Bridget Butler



## **A.2 Example project information sheet given to potential system users at user analysis stage**

### **RISK MANAGEMENT DECISIONS WITH REGARD TO HYDROCARBON POINT SOURCE GROUNDWATER POLLUTION - A KNOWLEDGE-BASED SYSTEM APPROACH - Bridget Butler**

First of all, what is a knowledge-based system (also known as expert systems too)? A knowledge-based system is just a computer programme that can utilise 'expert' knowledge to solve specific problems. It is a programme that solves problems like a human expert would, using the same information and reasoning patterns. The system I'm trying to develop will be a decision support system, it will not replace real human expertise only support decisions that real people have to make.

Why use a knowledge based system approach to the problem of groundwater pollution by hydrocarbons and what exactly is the problem from a regulators point of view ?

The NRA have certain statutory duties that they must undertake, such as the protection of groundwater. Groundwater pollution can arise from many sources in the UK but point source hydrocarbon pollution does present a problem to the NRA. This type of pollution can arise from fuel storage in general to petrol stations, solvent storage and the transport of hydrocarbons.

In order for the NRA to comply with their statutory duties they must 'do' something about the above sources of pollution. This could result in giving advice to external parties, tracing pollution sources, prosecuting offenders etc. The NRA must respond in the correct manner when presented with a situation.

The authority as a body only has so much time, money, personnel with the correct knowledge - to respond. Activities must be prioritised, sorted or categorised in some way in order to make the most effective use of authority resources to undertake their duty.

In order to prioritise effectively in relation to groundwater protection, pollution prevention or reducing the consequences of pollution, decisions should be made on a risk basis. Therefore some form of risk assessment needs to take place, preferably to the same methodology so all personnel are working to the same standards.

Once the risks have been assessed, risk management can be undertaken to reduce pollution potential at source, prevent/reduce the consequences of pollution. Activities can be prioritised or dealt with on a risk management basis rather than on an 'ad hoc' basis, improving efficiency in terms of statutory duty to protect groundwater.

These kinds of assessment and prioritisation decisions can be supported by a knowledge based system assisting in the decision process. This type of approach can improve efficiency and consistency by incorporating the correct models and asking the right questions in certain situations. The system to be developed will be a decision support system and will be designed to help in the decision making process, especially when the relevant human expert is not around.

### A.3 Example of the information sheet given to users taking part in the evaluation session

#### **HARRIS - Hydrocarbon and Risk Related Information System User Evaluation Session**

HARRIS is a computer-based tool designed to help you rank sites (such as petrol filling-stations) on the basis of risk to groundwater. It is not a multimedia model in that it only looks at groundwater and it is not a quantitative risk assessment model (so no sums). HARRIS enables you to rank and prioritise sites for action, even when you have a lot of information missing. The scenario set out below describes a site that is in a rather sensitive area. You have been asked to have a look at it and use HARRIS to rank the site. You are not investigating an actual spill or leak but the site's overall potential to pollute groundwater. Use HARRIS to answer these questions:

What risk number does HARRIS calculate for the site ?

What severity category has HARRIS put the site in ?

To get started click on 'OK' and then select 'Consult' from the menubar across the top of the screen and then 'Begin consultation' from the pull-down menu. Follow the instructions given.

#### **Scenario One - Petrol-Filling Station - In a large town**

This 'SuperPetrol' site is located at grid reference SE 329 878. The site was constructed in the mid-fifties and it was partially redeveloped in the early sixties when some additional tanks were installed. All tanks/pipework are steel (single-walled) and over 30 years old. No significant redevelopment has taken place since then and the forecourt is cracked and uneven. There was a leak recorded at the site two years ago when approximately 2000 litres of fuel was lost. There is a drinking water abstraction borehole approximately 225m away and it is not clear if the previous leak has had any impact on the borehole. The site is situated in a groundwater protection zone I on a major aquifer (sandstone).

#### *Other useful information:*

- Diesel and petrol are sold
- Total tank volume is approximately 75,000 litres
- Tankers use an offset fill-point which is above ground but not bunded properly
- Static leak detection is used
- New dispenser pumps have been installed (to BS 7117)
- There is an adequate interceptor at the site which drains to surface water
- Depth of unsaturated zone is 5m

#### **Scenario Two - Petrol-Filling Station - Busy city centre**

Located in an urban area surrounded by housing. The site is of a modern appearance and is self-service. There are six dispenser islands. Underground installations of pipework/tanks have been redeveloped in the last twenty years. Tanks are filled using off-set fills (aboveground and bunded). Site drainage does include an interceptor. There are no water courses nearby and the site is not situated in a groundwater protection zone.

## A.4 Example of the questionnaire given to users taking part in the evaluation session

## HARRIS - Hydrocarbon and Risk Related Information System - USER EVALUATION QUESTIONNAIRE

This questionnaire has been designed so that you can give me some specific guidance on how to make HARRIS easier to use and more effective. Even though HARRIS is a research prototype it should have given you an idea of what a fully developed system could do. The following questions should take between 10 and 20 minutes to complete. Circle the relevant answer or write in the space provided. Please leave the completed questionnaire with Dr Petts before you leave on Friday. Thank you for your time, I appreciate your help.

*System Performance Issues*

No.	Question	Yes	4	3	Not sure	2	No
1	Did the system allow you to categorise the example site satisfactorily ?	5	4	3	2	1	1
2	Did using HARRIS help you understand the source-pathway-target approach that is used in a risk assessment ?	5	4	3	2	1	1
3	Did using HARRIS help you to become familiar with the layout of a petrol filling-station and the hazards such a site may present to groundwater ?	5	4	3	2	1	1
4	Is the type of information that HARRIS uses to categorise a site the type of information that you would use to do the same thing manually ?	5	4	3	2	1	1
5	HARRIS can categorise sites so they can be prioritised - is this useful ?	5	4	3	2	1	1
6	Do you think HARRIS would be useful to non-Environment Agency staff (if they were responsible for assessing petrol filling-stations in some way) such as: (a) an environmental consultant ? (b) an environmental health officer ? (c) a company environmental manager ?	5	4	3	2	1	1
7	Did you have any difficulties in knowing what to do next ?	5	4	3	2	1	1

8 Did you need any external help to use the system ?  
If yes, at which point ?

Yes No

--

9 Were the questions/selections presented by HARRIS appropriate to this problem ?  
If no, which ones and why not

Yes No

--

10 Was there any aspect of HARRIS that you found irritating, even though it did not interfere with the final site categorisation ? If yes, which aspect ?

Yes

No

--

11 Was there any aspect of HARRIS that you found particularly difficult to understand?      Yes      No  
If yes, which aspect?

12 As a system user, what do you think are the most positive aspects of HARRIS?

13 What are the most negative aspects of HARRIS?

14 What major modifications or additions would make HARRIS more accessible and useful to the user?

*Information-Interaction Issues*

No.	Question	Yes	4	Not sure	2	No
15	Were the user instructions for HARRIS useful ?	5	4	3	2	1
16	If you used them, were the explanations offered by HARRIS generally sufficient ?	5	4	3	2	1
17	Did the system respond quickly enough ?	5	4	3	2	1
18	Would more graphical information be useful ?	5	4	3	2	1
19	Do you think that the general appearance of HARRIS was satisfactory ?	5	4	3	2	1

20 Could you understand the questions that HARRIS asked you ?  
If no, which questions and why ?

21 Did you feel that as a learning-tool about point-source ground-water pollution, that the information provided by HARRIS is adequate ?  
If not, what information functions need to added ?

22 Did you feel that in terms of the recommendations that HARRIS made when categorising sites, that the information provided by HARRIS is adequate? If not, what information/details need to be added?

*Physical Issues*

No.	Question	Yes	4	Not sure	2	No
23	Is a mouse operated program preferable to a key-board operated program?	5	4	3	2	1
24	Could you follow the screen layout?	5	4	3	2	1
25	Did you have any difficulties in: (a) using the buttons? (b) answering questions posed by HARRIS (e.g., trouble selecting the answer)? (c) entering text/values?	5	4	3	2	1

Your attitudes to HARRIS

No.	Question	Strongly Agree	Agree	Not sure	Disagree	Strongly Disagree
26	I was confident using HARRIS	5	4	3	2	1
27	I thought that HARRIS showed too much inconsistency	5	4	3	2	1
28	I thought HARRIS was easy to use	5	4	3	2	1
No.	Question	Strongly Agree	Agree	Not sure	Disagree	Strongly Disagree
29	I needed to learn a lot of things before I could use HARRIS	5	4	3	2	1
30	I thought that the tasks carried out by HARRIS were well integrated	5	4	3	2	1
31	I thought that HARRIS was far too complex	5	4	3	2	1
32	I would be able to use HARRIS in my working environment if I needed to	5	4	3	2	1
33	I thought HARRIS was awkward to use	5	4	3	2	1
34	I think that most people (even those with no expertise in groundwater protection) could learn to use HARRIS quite quickly	5	4	3	2	1
35	I think that I would need the support of a groundwater specialist before I could use HARRIS	5	4	3	2	1

Do you have any further comments you wish to make ?



## APPENDIX B

### KNOWLEDGE ACQUISITION PHASE

#### B.1 Protocol analysis - example of a case study used with the principal expert

The questions asked of the principal expert were; detail the information required and procedures that would be followed, in order to deal with the problem of groundwater or potential groundwater pollution at this site, using a risk-based approach.

This information was given to the expert in writing:

##### Case 1 - Solvent pollution from factory site

Site came to light due to a spillage of tetrachloroethene, tetrachloroethylene (PCE) at a textile factory. Subsequently found that effluent from a PCE/water separation process had been disposed of to soakaway with no consent to discharge. This was a continual process with the water draining off saturated with PCE and if the PCE wasn't manually drained off regularly, PCE as well.

On investigation all the other surrounding factories were visited, only one used 'any significant amount of PCE'. A schematic diagram of the site was also given to the expert with all place names etc. masked out.

The following information was available to the expert if required:

##### *General Information*

Site is on 'superficial deposits' overlying sandstone

**Geology** - sandstone (Fell Sandstone Group) Outcrop is thinner around the site area (Berwick) so topography is 'smoother'.

No mapping of individual sandstones within Group but boreholes have been sunk recently to west of site to investigate water resources. These show that the major sandstone units are separated by laterally persistent mudstones (locally known as marl) with an approximate sandstone:mudstone equal.

Sandstones often have a 'lens shaped geometry' up to 30m thick, sometimes rapid lateral thinning.

**Targets** - four large public water supply boreholes within 6km of site (yield 2500 m<sup>3</sup>/d) Boreholes penetrate several of the sandstone units, mudstones form effective ('aquicludes' preventing hydraulic continuity between sandstones). Water is generally of a high quality requiring only the basic treatment.

In addition there are two production boreholes belonging to a grain malting company within 100m of the soakaway, 'down the dip of the strata'. These two boreholes are licensed to abstract 1500 m<sup>3</sup>/d and are 107m and 95m deep, the shallower one supplying 75% of supply. The boreholes were sampled, the deeper borehole providing 25% of supply had a level of 60µg/l of PCE, with the shallower borehole, (75% of supply) had a trace (< 1 µg/l).

## B.2 List of concept words elicited from the principal expert and used in the card sorts with other participants

Table B.1: Concept words and corresponding card number

Card No.	Concept
1	Permeability of aquifer high
2	Strata are not layered
3	Strata are layered
4	Travel time
5	Permeability of aquifer medium
6	Permeability of aquifer low
7	Underground fuel tank (contained)
8	Volume of spill is < 10,000 litres
9	Volume of spill is > 10,000 litres
10	Groundwater vulnerability - minor aquifer
11	Leakage monitoring system
12	Containment facilities - pea gravel only
13	Groundwater samples do not meet quality standards
14	No targets within 500 m
15	Well logs
16	Diesel spill
17	Containment facilities - concrete surround only
18	Underground fuel tank (uncontained)
19	Concentration of contaminant high
20	Target within 500 m
21	Groundwater vulnerability - non- aquifer
22	List I substances
23	Information from 'polluter' good
24	Groundwater samples do meet quality standards
25	Sample (non-weathered)
26	Specialist groundwater staff available for communication
27	Sampling
28	Groundwater flow is high
29	Removal of contaminated strata
30	Groundwater vulnerability - major aquifer
31	List II substances
32	Access for investigation had
33	Red List substances
34	Specialist groundwater staff not available for communication
35	Sample (weathered)
36	Information from 'polluter' unreliable
37	Drinking water abstraction < 1 km away
38	Outside specialists (BGS etc.) available
39	Remediation - boreholes, pump and treat
40	Drinking water abstraction > 1 km away
41	Depth to water table 5 m
42	Volumetric loading is not widely spread
43	Surface water course near
44	No unsaturated zone
45	Attenuation
46	Ordnance Survey maps
47	Mainly clay strata
48	Investigation in rural area
49	Company contingency plan not in place

Table B.1 Contd.	
Card No.	Concept
50	Strata are not fissured
51	Access for investigation good
52	Abstraction for agricultural, industrial use only close
53	Depth to water table 5 m
54	Volumetric loading is widely spread
55	Abstraction for agricultural, industrial use only far away
56	Unsaturated zone present
57	Dilution factor high
58	Strata are fissured
59	Mainly sandstone strata
60	Investigation in urban area
61	Mineral oil spill
62	Local geology
63	Local knowledge culverts/drains etc.
64	Soil type
65	Benzene
66	Petrol spill
67	Type of leak - long term seepage (chronic)
68	Xylene
69	Toluene
70	Type of leak - acute leakage
71	Company contingency plan in place
72	BTEX compounds
73	High mobility pollutant
74	MTBE additives
75	Fuel oil spill
76	Petrol spill on soil surface
77	Diesel spill on soil surface
78	Low mobility pollutant
79	Petrol spill not onto soil surface
80	Diesel spill not onto soil surface
81	Surface water course not nearby
82	Groundwater flow is low
83	Concentration of contaminants - low
84	Remediation - dig out and remove
85	Remediation strategy - do nothing
86	Dilution factor - low
87	Inform borehole owner of problem
88	Inform water company of problem
89	Remediation - trench and remove
90	Intrinsic bioremediation

## B.3 Concepts used as part of the risk-rating exercise with related scores

Table B.2: Concepts with related scores and prioritisation categories from the risk rating exercise

CONCEPT	SCORE	CATEGORY
<i>Table 1 - Source Terms - Not specific to petrol-filling stations</i>		
Information on incident from polluter is unreliable	11.2	Medium-high
Information on incident from polluter is reliable	5.2	Medium-low
Concentration of contaminants is high	11.8	Medium-high
Concentration of contaminants low	5	Medium-low
Solubility of contaminants is medium (1-1000 mg/l in water)	8.8	Medium
Solubility of contaminants is high (>1000 mg/l in water)	11.4	Medium-high
Solubility of contaminants is low (< 1 mg/l in water)	5.6	Medium-low
Non-persistent contaminant (half-life in groundwater <100 days)	9	Medium
Persistent contaminant (half life in groundwater > 100 days)	12.6	Medium-high
Contaminant is immiscible - can form NAPL	9	Medium
Contaminant not immiscible - does not form NAPL	9.4	Medium
Volume of pollutant is > 10,000 litres	13.8	High
Volume of spill is < 10,000 litres	10.6	Medium-high
Chronic leak, long term seepage	11.6	Medium-high
Acute leak, short term release	13.4	High
Volumetric loading of pollutant is on small area of land	12	Medium-high
Volumetric loading of pollutant is spread over large amount of land	9.6	Medium
High mobility pollutant	13.2	High
Low mobility pollutant	7	Medium
List I substances	11.6	Medium-high
List II substances	10.6	Medium-high
Red list substances	12.4	Medium-high
Mineral oil spill	8.2	Medium
Fuel oil spill	9	Medium
Diesel spill	9	Medium
Petrol spill	9.6	Medium
BTEX compounds	9.4	Medium
MTBE additive	10	Medium-high
Toluene	9.2	Medium
Benzene	9.6	Medium
Xylene	9.4	Medium
Ethylbenzene	9.4	Medium
Pesticides/herbicides	11.8	Medium-high
Construction materials, waste wood etc.	5.6	Medium-low
Foundry sand	6.6	Medium-low
Food processing waste	10	Medium-high
Agricultural waste (not pesticides)	9.4	Medium
Petrol spill below ground (below soil surface)	12.2	Medium-high
Petrol spill above ground (onto soil surface)	10	Medium-high
Diesel spill below soil surface	11.6	Medium high
Diesel spill on soil surface	10	Medium high
Sample (weathered or non-weathered)	5	Medium-low
Remediation strategy - intrinsic bioremediation	10.6	Medium-high
Remediation strategy - do nothing	10.8	Medium-high
Remediation strategy - dig out and remove	6.8	Medium-low
Remediation strategy - trench and remove	7.6	Medium
Remediation strategy - sink boreholes, pump and treat	8.2	Medium
Inform water company of problem	6.2	Medium-low
Inform borehole owner of problem	6	Medium-low
Specialist groundwater staff not available to help	6.4	Medium-low

Table B.2 Contd.		
CONCEPT	SCORE	
Specialist groundwater staff are available to help	4.4	Medium-low
Outside specialists are available to help	4.2	Medium-low
<i>Table 2 - Source terms specific to petrol filling stations</i>		
Site throughput > 5 million litres per year	6.2	Medium-low
Site throughput 500,000 & 5 million litres per year	6	Medium-low
Site throughput < 500,000 litres per year	6	Medium-low
Petrol station in GP Zone I	12	Medium-high
Petrol station in GP Zone II	9.8	Medium
Petrol station in GP Zone III	7.8	Medium
<i>Terms associated with the delivery of petrol</i>		
Dispensing/delivery area concreted, joints sealed, no cracking	4.8	Medium-low
Dispensing/delivery area concreted, in poor condition, visible damage	8.2	Medium
Spill kit available & someone trained to use it	2.8	Low
No spill kit or no one available who can use it	7.2	Medium
Off set fill to tanks above ground, in bunded area	3.8	Low
Off set fill to tanks above ground, not in bunded area	6.2	Medium-low
Offset fill to tanks below ground, with secondary containment	4	Medium-low
Offset fill to tanks below ground, no secondary containment	6.4	Medium-low
Direct tank fill below ground	6.6	Medium-low
Tanks have overfill protection device	3.2	Low
Tanks have no overfill protection device	6	Medium-low
No joints outside of chambers on site	3.4	Low
<i>Table 3 - Terms associated with storage &amp; distribution of petrol</i>		
Pipework system for underground tank uses pressure to deliver product	5.4	Medium-low
Pipework system for underground tank uses suction/siphon system to deliver product	6.8	Medium-low
Pipework - single skin steel	6	Medium-low
Pipework - single skin GRP	4.4	Medium-low
Pipework - single skin plastic (permeability > 2g/m <sup>2</sup> )	5.2	Medium-low
Pipework - single skin plastic (permeability < 2g/m <sup>2</sup> )	4.2	Medium-low
Secondary containment to pipework	2.8	Low
Leak detection - fuel lines, none	6.8	Medium-low
Leak detection - fuel lines, internal	4.2	Medium-low
Leak detection - fuel lines, external	4	Medium-low
Pipework - over 30 years old	7.4	Medium
Pipework - 20-30 years old	5.6	Medium-low
Pipework - < 20 years old	4	Medium-low
Tank/pipework system tested annually	3.2	Low
Tank/pipework system tested every 5 years	4.8	Medium-low
Tank/pipework system tested every 10 years	6.4	Medium-low
Abandonment of old tanks - unknown	7.4	Medium
Abandonment of old tanks - liquid fuel seal	7.2	Medium
Abandonment of old tanks - liquid seal (water)	4.4	Medium-low
Abandonment of old tanks - cleaned, backfilled with sand, foam, or concrete	2.6	Low
Above ground storage tanks on site (bundled adequately)	4	Medium-low
Above ground storage tanks on site (not bundled adequately)	8	Medium
Underground fuel tank (contained)	5.6	Medium-low
Underground fuel tank (not contained)	7.8	Medium
Underground tanks with concrete surround	6	Medium-low
Underground tanks with pea gravel surround	8	Medium
Underground tanks with foam surround	6.8	Medium-low
Single skin steel tank	5.8	Medium-low
Double skin steel tank	3	Low

Table B.2 Contd.		
CONCEPT	SCORE	CATEGORY
Steel tank, cathodically protected	4.6	Medium-low
Steel tank, no cathodic protection	6.2	Medium-low
Single skin composite material	5.4	Medium-low
Interstitial monitoring of tanks	3.8	Low
Interstitial monitoring of pipework/fuel lines	3.4	Low
Tank construction - GRP or double skin steel (no continuous monitoring)	4.4	Medium-low
Tank construction - double skin plus continuous interstitial monitoring	2.4	Low
Tank gauging - manual dipping	7	Medium
Tank gauging - continuous statistical leak detection	4.4	Medium-low
Tank gauging - static leak detection	5.2	Medium-low
Tank gauging - automatic wet stock reconciliation	3.4	Low
Monitoring wells present at site	3.2	Low
Monitoring wells - not checked	4.8	Medium-low
Monitoring wells - checked manually	3.2	Low
Monitoring wells - checked automatically	2.8	Low
Maximum total operational tank volume on site < 50,000 l	4.8	Medium-low
Maximum total operational tank volume on site 50,000 to 100,000 l	5.2	Medium-low
Maximum total operational tank volume on site > 100,000 l	5.6	Medium-low
Age of underground tanks > 30 years	8.8	Medium
Age of underground tanks 20-30 years	7	Medium
Age of underground tanks < 20 years	5.2	Medium-low
<i>Table 4 - Terms associated with dispensing of petrol</i>		
Dispensing equipment complies with BS 7117	3.2	Low
Dispensing equipment does not comply with recognised standard	6.2	Medium-low
Leak detection fitted - dispenser sumps	3	Low
Leak detection not fitted to dispenser sumps	6	Medium-low
Pump islands are sealed at junction forecourt/island	3	Low
Pump islands not sealed at forecourt/island junction or seal in poor condition	6.2	Medium-low
<i>Table 5 - Petrol filling station control measures</i>		
Surface water/interceptor drainage discharges to soakaway	8.2	Medium
Surface water/interceptor drainage discharges to surface water	10	Medium high
Surface water/interceptor drainage discharges to foul sewer	5.2	Medium-low
Drainage system can be isolated manually	4.8	Medium-low
Drainage system can be isolated automatically	4	Medium-low
Drainage system can not be isolated	8.4	Medium
No interceptor on site	9.4	Medium
Interceptor present but no evidence that inspected/maintained properly	8.2	Medium
Interceptor in place - adequate for site	4.2	Medium-low
Interceptor - Class I with automatic closure & coalescing filter	3.6	Low
Interceptor - Class II	4.4	Medium-low
Interceptor - 2 chamber brick	5	Medium-low
Interceptor - 3 chamber brick/fibreglass	4.2	Medium-low
Interceptor - superceptor	2.6	Low
Drainage system pressure tested every 2 years or less	3.4	Low
Drainage system pressure tested every 2-5 years	5.2	Medium-low
Drainage system pressure tested every 6-10 years	6.2	Medium-low
Drainage system pressure tested > 10 years	7.6	Medium
Site specific contingency plan	3.6	Low
No site specific contingency plan	8	Medium
Leak detection system has automatic alarm, procedure to follow when alarm goes off	3.2	Low
Leak detection system present, no automatic alarm or no procedure to follow when it does go off	6.6	Medium low

Table B.2 Contd.		
CONCEPT	SCORE	CATEGORY
Site is part of an EMAS programme & site management understand programme	3.4	Low
Site is not part of an EMAS programme or site management unaware of function of programme	5.6	Medium-low
<i>Table 6 - Pathway terms</i>		
Local geology	4.8	Medium-low
OS maps	4.6	Medium-low
Groundwater vulnerability - non aquifer	4.8	Medium-low
Groundwater vulnerability - minor aquifer	8.2	Medium
Groundwater vulnerability - major aquifer	10.8	Medium-high
High permeability of underlying aquifer	10.4	Medium-high
Medium permeability of underlying aquifer	7.6	Medium
Low permeability of underlying aquifer	5.6	Medium-low
High annual rainfall (> 1000 mm)	5.2	Medium-low
Annual rainfall 200-400 mm	5.2	Medium-low
Low annual rainfall (< 200 mm)	5	Medium-low
Dilution factor is low	6.8	Medium-low
Dilution factor is high	5.6	Medium-low
Soil type	5.2	Medium-low
Depth to water table > 5 m	8	Medium
Depth to water table < 5 m	9.6	Medium
Depth to regional groundwater table <10m	9	Medium
Depth to regional groundwater table 10-25m	7.2	Medium
Depth to regional groundwater table >25m	6	Medium-low
Thickness of low permeability clay cover 0-3 m	9.2	Medium
Thickness of low permeability clay cover 3-5 m	7.4	Medium
Thickness of low permeability clay cover 5-8m	5.4	Medium-low
Thickness of low permeability clay cover > 8m	4	Medium-low
Depth of low permeability drift <5m	8	Medium
Depth of low permeability drift 5-10m	5.4	Medium-low
Depth of low permeability drift >10m	4.4	Medium-low
Strata are not fissured	5.4	Medium-low
Strata are fissured	8	Medium
Strata are layered	6.2	Medium-low
Strata are not layered	5.8	Medium-low
Mainly clay strata	5	Medium-low
Mainly sandstone strata	8.6	Medium
Mainly limestone strata	9.75	Medium
No unsaturated zone present	9.6	Medium
Unsaturated zone present	8.6	Medium
Groundwater flow is high	8.8	Medium
Groundwater flow is low	7.6	Medium
Intergranular flow, <10m unsaturated zone	8.4	Medium
Intergranular flow, 10-25m unsaturated zone	7.6	Medium
Intergranular flow, >25m unsaturated zone	7.2	Medium
Fissure flow, <10m unsaturated zone	9.8	Medium
Fissure flow, 10-20m unsaturated zone	8.6	Medium
Fissure flow, 20-50m unsaturated zone	8.4	Medium
Hydraulic conductivity of unsaturated zone > 10 <sup>-4</sup> cm/sec (sand/gravels)	10.4	Medium-high
Hydraulic conductivity of unsaturated zone 10 <sup>-4</sup> to 10 <sup>-6</sup> cm/sec (sandstones)	8.4	Medium
Hydraulic conductivity of unsaturated zone < 10 <sup>-6</sup> cm/sec (clays)	6.2	Medium-low
Permeable strata - K <sub>v</sub> ≥ 1mm/day (K <sub>v</sub> is vertical coefficient of permeability)	7.2	Medium
Low permeability strata - K <sub>v</sub> < 1mm/day (K <sub>v</sub> is vertical coefficient of permeability)	8.6	Medium

Table B.2 Contd.		
CONCEPT	SCORE	CATEGORY
Tunnel/mains services/underground works beneath or within 25m of site	9	Medium
No tunnel/mains services/ underground works beneath or within 25m of site	4	Medium-low
Local knowledge of culverts/drains available	5.6	Medium-low
Well log information available	3.2	Low
<i>Table 7 - Target terms</i>		
No targets within 500 m	5.8	Medium-low
Target within 500m	10.6	Medium-high
No residential building within 30m	6.6	Medium-low
Residential building without basement within 30m	9.6	Medium
Residential building with basement within 30m	11	Medium-high
SSSI (or equivalent) within 200m	10.4	Medium-high
No surface water bodies nearby	5.4	Medium-low
Surface water body nearby	9.4	Medium
Surface water body within 50m	12.4	Medium-high
EA water quality objective of nearby water body - a	10.6	Medium-high
EA water quality objective of nearby water body - b	10.2	Medium-high
EA water quality objective of nearby water body - c	9.8	Medium
EA water quality objective of nearby water body - d	9	Medium
EA water quality objective of nearby water body - e	8.6	Medium
Water abstraction point within 200m	14	High
Water abstraction point 200m - 2 km	11	Medium-high
Water abstraction point 2.01 - 5km away	7.6	Medium
Water abstraction point > 5km away	6	Medium-low
Drinking water abstraction potentially affected - no alternative supply	14.6	High
Drinking water abstraction potentially affected - alternative supply difficult to provide	14.6	High
Drinking water abstraction potentially affected - alternative supply available	14.2	High
Abstraction for agricultural/industrial use not close by	6.8	Medium-low
Abstraction for agricultural/industrial use nearby	11.4	Medium-high
Surrounding land mainly industrial	8.2	Medium
Surrounding land mainly residential	10	Medium-high
Surrounding land mainly agricultural	6.6	Medium-low
Surrounding land mainly mixed	8.2	Medium



## APPENDIX C

### HARRIS INFORMATION REQUIREMENTS, EXAMPLE OUTCOMES AND PROTOTYPE KNOWLEDGE-BASE CODE

#### C.1 HARRIS Information Requirements - User Input

Table C.1 presents the sections of HARRIS with the relevant information requirements of the system. Also illustrated is any user help or explanations for each section.

**Table C.1:** Information requirements of HARRIS and associated explanations and user help

Process Stages	System Information Requirements	Associated Explanations/User Help
System introduction and user instructions		<ul style="list-style-type: none"> <li>• Risk-based approach to decision-making</li> </ul>
<b>Stage 1 - IDENTIFY SITE</b>		
	<ul style="list-style-type: none"> <li>• Site name &amp; location</li> <li>• Type of site to be investigated</li> <li>• Grid reference</li> <li>• Assessment type - actual incident e.g., fuel spill or assessment for site prioritisation</li> </ul>	<ul style="list-style-type: none"> <li>• Reasons for asking for site name &amp; location</li> <li>• HARRIS currently prioritises retail petrol-filling stations only</li> <li>• Site 'base risk' number</li> <li>• Reasons for recording of grid reference</li> <li>• HARRIS currently set up to carry out assessment for site prioritisation purposes</li> </ul>
<b>Stage 2 - ANALYSIS OF ACTIVITIES</b>		
	<ul style="list-style-type: none"> <li>• Type of activities carried out at the site - delivery, storage and dispensing of fuel</li> </ul>	<ul style="list-style-type: none"> <li>• Description of typical activities on this type of site (petrol-filling station)</li> </ul>
<b>Stage 3 - IDENTIFY HAZARDS</b>		
<i>Product Hazard</i>  <i>Delivery Hazard</i>  <i>Storage Hazards</i>	<ul style="list-style-type: none"> <li>• Type of products stored at the site</li> <li>• Method of fuel delivery</li> <li>• Type of tank over-fill protection</li> <li>• Condition of delivery area (concrete pad)</li> <li>• Operational tank volume</li> <li>• Tank construction and age</li> <li>• Pipework construction and age</li> <li>• Tank/pipework testing interval</li> <li>• Leak detection system used</li> </ul>	<ul style="list-style-type: none"> <li>• Types of product that may be found &amp; their properties</li> <li>• Types of method used to delivery fuel</li> <li>• Description of what over-fill protection is</li> <li>• Explanation why this could be useful information</li> <li>• What operational tank volume is and its possible significance</li> <li>• Types of construction material, significance of age of tank, corrosion protection</li> <li>• Types of construction material, significance of age of pipework, corrosion protection</li> <li>• Why systems are tested and significance of interval</li> <li>• Types of system available</li> </ul>

Table C.1 Contd		
Process Stages	System Information Requirements	Associated Explanations/User Help
<i>Dispensing Hazards</i>	<ul style="list-style-type: none"> <li>Pump type</li> <li>Condition of pump island seals</li> <li>Fuel distribution system</li> </ul>	<ul style="list-style-type: none"> <li>Types of pump available</li> <li>Significance of parameter</li> <li>Systems available and significance of each type</li> </ul>
<i>Site Control Procedures</i>	<ul style="list-style-type: none"> <li>Presence and adequacy of interceptor</li> <li>Drainage system used and testing interval</li> </ul>	<ul style="list-style-type: none"> <li>Types of interceptor, explanation of how to ensure adequacy</li> <li>Types available, significance of testing</li> </ul>
<b>Stage 4 - EXPOSURE OR HAZARD PATHWAY</b>		
<i>Target Characterisation</i>  <i>Pathway Characterisation</i>	<ul style="list-style-type: none"> <li>History of past incidents at the site</li> <li>Type of target that could be impacted by the site</li> <li>Target location</li> <li>If identified target is a drinking water abstraction - type of source protection zone</li> <li>Strata underlying site</li> <li>Type of groundwater flow</li> <li>Depth of unsaturated zone</li> <li>Permeability of aquifer</li> <li>Hydraulic conductivity of unsaturated zone</li> <li>Type of aquifer</li> </ul>	<ul style="list-style-type: none"> <li>Significance of information</li> <li>Description of target types</li> <li>Description of target types</li> <li>Significance of target type and proximity to the site</li> <li>Description of source protection zones</li> <li>Description of generic strata and significance</li> <li>Description of groundwater flow, significance of different type</li> <li>Description of unsaturated zone and significance of depth</li> <li>Description of permeability</li> <li>Description of parameter and its significance</li> <li>Concept of groundwater vulnerability</li> <li>Typical aquifers in England and Wales</li> </ul>
<b>Stage 5 - PREDICTION OF THE CONSEQUENCES &amp; Stage 6 - RISK CALCULATIONS</b>		
	<ul style="list-style-type: none"> <li>Outcome of assessment process</li> <li>Site categorisation carried out by system</li> </ul>	<ul style="list-style-type: none"> <li>Description of potential outcomes</li> <li>Explanation of site prioritisation categories</li> </ul>
<b>Stage 7 - RISK ACCEPTABILITY</b>		
	<ul style="list-style-type: none"> <li>Is risk acceptable? User to decide guided by current policy</li> </ul>	<ul style="list-style-type: none"> <li>Current policy on site development etc.</li> </ul>
<b>Stage 8 - RISK MANAGEMENT ACTIONS</b>		
	<ul style="list-style-type: none"> <li>Suggested actions dependant on information supplied by user - guidance only not recommendations</li> </ul>	<ul style="list-style-type: none"> <li>Potential areas for risk reduction</li> <li>Explanation for the need for monitoring and auditing process</li> </ul>
End of consultation	<ul style="list-style-type: none"> <li>User invited to carry out another assessment</li> </ul>	

## C.2 HARRIS Outcomes - Worst-Case, Best-Case and Case of User Uncertainty

Table C.2 shows the outcome of using HARRIS to score a best-case, a worst-case and a case of user uncertainty. The worst-case score represents the maximum score any site could achieve using HARRIS and the best-case score represents the minimum score. In reality these sites would not exist due to an unlikely combination of parameters.

**Table C.2: HARRIS scenarios representing worst-case, best-case and case of user uncertainty**

System Parameter	Worst-Case Score	User Uncertain	Best Case Score
<b>Stage 1 - IDENTIFY SITE</b>			
Type of site to be investigated - petrol-filling station	10	10	10
<b>Stage 2 - ANALYSIS OF ACTIVITIES</b>			
Type of activities carried out at the site delivery, storage and dispensing of fuel	-	-	-
<b>Stage 3 - IDENTIFY HAZARDS</b>			
<i>Product Hazard</i>			
Type of products stored at the site			
• Petrol	12.2	12.2	0
• Diesel	11.6	11.6	0
• Other products (e.g. oil)	8.6	0	0
<i>Delivery Hazard</i>			
Method of fuel delivery			
• Direct fill	6.6	-	-
• Off-set fill above-ground, with bunding	-	-	3.8
• Uncertain	-	6	-
Type of tank over-fill protection			
• Present	6	-	-
• Not present	-	-	3.2
• Uncertain	-	3.2	-
Condition of delivery area (concrete pad)			
• Good	-	-	4.8
• Poor	8.2	-	-
• Uncertain	-	6.5	-
<i>Storage Hazards</i>			
Operational tank volume			
• > 100,000 litres	5.6	-	-
• < 50,000 litres	-	-	4.8
• Uncertain - located rural/minor routes	-	4.8	-
Tank construction and age			
• Single steel, no cathodic protection	9	-	-
• Steel with polyurethane jacket	-	-	2
• Uncertain tank construction	-	5.8	-
• Uncertain corrosion protection	-	3.2	-
• Tank age > 30 years	8.8	-	-
• Tank age < 20 years	-	-	5.2
• Uncertain tank age	-	7	-
Pipework construction and age			
• Metallic, no secondary containment, no corrosion protection	19.2	-	-
• Non-metallic, secondary containment	-	-	7.2

Table C.2 Contd.			
System Parameter	Worst-Case Score	User Uncertain	Best Case Score
• Uncertain construction	-	19.2	-
• Pipework age > 30 years	7.4	-	-
• Pipework age < 20 years	-	-	4
• Uncertain pipework age	-	5.9	-
<b>Tank/pipework testing interval</b>			
• No evidence of testing in last 10 years	8	-	-
• Every 2 years or less	-	-	3.2
• Uncertain	-	5.6	-
<b>Leak detection system used</b>			
• Manual tank dipping	7	-	-
• Automatic wetstock reconciliation	-	-	3.4
• Uncertain	-	5.2	-
<b>Dispensing Hazards</b>			
<b>Pump type</b>			
• Not to standard	6.2	-	-
• To BS7117	-	-	3.2
• Uncertain - new modern site	-	3.2	-
<b>Condition of pump island seals</b>			
• Poor	6.2	-	-
• Good	-	-	3
• Uncertain	-	6.2	-
<b>Fuel distribution system</b>			
• Pressurised	6.8	-	-
• Suction/siphon	-	-	5.4
• Uncertain	-	5.4	-
<b>Site Control Procedures</b>			
<b>Presence and adequacy of interceptor</b>			
• None present	9.4	-	-
• Present and adequate	-	-	4.2
• Uncertain	-	6.8	-
<b>Drainage system drains to:</b>			
• Surface water	10	-	-
• Foul sewer	-	-	5.2
• Uncertain	-	7.6	-
<b>Drainage system isolation</b>			
• Can not be isolated	8.4	-	-
• Can be isolated	-	-	4
• Uncertain	-	8.4	-
<b>Drainage system testing interval</b>			
• No evidence of testing in last 10 years	7.6	-	-
• Tested every 2 years or less	-	-	3.4
• Uncertain	-	5	-
<b>Stage 4 - EXPOSURE OR HAZARD PATHWAY</b>			
<b>Target Characterisation</b>			
<b>History of past incidents at the site</b>			
• Petroleum release, > 10,000 litres	26	-	-
• No documentary evidence of past release	-	-	5
• Uncertain product release	-	12.2	-
• Uncertain volume released	-	7.4	-
<b>Target definitely impacted by a previous incident</b>			
• Drinking water abstraction	29.6	-	-
• Groundwater	-	-	(25)*

Table C.2 Contd.			
System Parameter	Worst-Case Score	User Uncertain	Best Case Score
• Uncertain target impacted	-	29.6	-
Targets identified currently			
• Drinking water abstraction, < 200m away	28.6	-	-
• Groundwater, unsaturated zone > 51m	-	-	10
• Uncertain	-	28.6	-
<i>Pathway Characterisation</i>			
If identified target is a drinking water abstraction - type of source protection zone			
• SPZ I	12	-	-
• SPZ III	-	-	(7.8)**
• Uncertain	-	9.9	-
Strata underlying site			
• Mainly chalk	9.8	-	-
• Mainly clay	-	-	5
• Uncertain	-	7.4	-
Type of groundwater flow & depth of unsaturated zone			
• Fissure flow, < 10m unsaturated zone	19.1	-	-
• Intergranular flow, > 51m unsaturated zone	-	-	0
• Uncertain	-	19.1	-
Permeability of aquifer			
• High (sands/gravels)	10.4	-	-
• Low (clays)	-	-	5.6
• Uncertain	-	10.4	-
Hydraulic conductivity of unsaturated zone			
• Sands/gravels (> 10 <sup>-4</sup> cm/sec)	10.4	-	-
• Clays (< 10 <sup>-6</sup> cm/sec)	-	-	6.2
• Uncertain	-	10.4	-
Type of aquifer			
Chalk	10.8	-	-
Clays	-	-	4.8
Uncertain	-	10.8	-
<b>TOTAL SCORE</b>	<b>339.5</b>	<b>294.6</b>	<b>116.6</b>
Prioritisation Category	High	Medium-High	Low

\* A target need not have been impacted by the site in the past so score need not be included in a best-case scenario

\*\* Source protection zones are only designated for drinking water abstractions - if the most sensitive target is a surface water body, there will be no SPZ designation and score will not be included in a 'best-case scenario'

### C.3 Example HARRIS Scores for Each Prioritisation Category

HARRIS is able to classify sites into five categorisations in addition to providing an overall 'risk number' for the site. Table C.3 shows some example properties of sites that would be categorised into each of the 'significance to groundwater' categories.

**Table C.3: Example HARRIS categorisations and associated scores**

Parameters	Significance Categories				
	High	Medium-High	Medium	Medium-Low	Low
<b>Stage 1 - Identify Site</b>					
Petrol-filling station	10	10	10	10	10
<b>Stage 2 - Analysis of Activities</b>	-	-	-	-	-
<b>Stage 3 - Identify Hazards</b>					
<i>Product Hazard</i>					
Type of product stored at site					
• No products	-	-	-	-	-
• Other products only (oil)	-	-	-	-	-
• Diesel only	-	-	-	-	-
• Petroleum only	-	-	-	12.2	12.2
• Unsure	-	-	-	-	-
• Petroleum & diesel	-	23.8	23.8	-	-
• Petroleum, diesel & other	32.4	-	-	-	-
<i>Delivery Hazard</i>					
Method of fuel delivery					
• Off-set, above, bunded	-	-	-	-	3.8
• Off-set, below, secondary containment	-	-	-	4	-
• Unsure	-	-	-	-	-
• Off-set, above, no bunding	-	-	6.2	-	-
• Off-set, below, no secondary containment	-	6.4	-	-	-
• Direct fill	6.6	-	-	-	-
Tank over-fill protection					
• Yes	-	-	3.2	3.2	3.2
• No	6	6	-	-	-
• Unsure	-	-	-	-	-
Condition of delivery area					
• Good	-	-	-	-	4.8
• Poor	8.2	8.2	-	-	-
• Unsure	-	-	6.5	6.5	-
<i>Storage Hazards</i>					
Tank volume					
• > 100,000 litres	5.6	5.6	-	-	-
• 50-100,000 litres	-	-	5.2	5.2	-
• < 50,000 litres	-	-	-	-	4.8
• Uncertain - motorways/major routes	-	-	-	-	-
• Uncertain - town/supermarkets	-	-	-	-	-
• Uncertain - rural/minor routes	-	-	-	-	-
Tank construction					
• Steel & polyurethane jacket	-	-	-	-	2
• GRP	-	-	-	4.4	-
• Double steel & corrosion protection	-	-	-	-	-

Table C.3 Contd.					
Parameters	Significance Categories				
	High	Medium-High	Medium	Medium-Low	Low
• Double steel, unsure corrosion protection	-	-	-	-	-
• Double steel, no corrosion protection	-	-	-	-	-
• Single steel & corrosion protection	-	-	7.4	-	-
• Single steel, no corrosion protection	-	9	-	-	-
• Single steel, unsure corrosion protection	-	-	-	-	-
• Unknown material, unsure corrosion protection	9	-	-	-	-
<b>Tank age</b>					
• > 30 years	8.8	8.8	-	-	-
• 20 - 30 years	-	-	7	7	-
• < 20 years	-	-	-	-	5.2
• Unsure	-	-	-	-	-
<b>Pipework construction</b>					
• Non metallic, & secondary containment	-	-	-	-	7.2
• Non metallic, no secondary containment	-	-	-	-	-
• Non-metallic, unsure secondary containment	-	-	-	-	-
• Metallic, & secondary containment & corrosion protection	-	-	-	13.2	-
• Metallic, no secondary containment & corrosion protection	-	-	-	-	-
• Metallic, unsure secondary containment & corrosion protection	-	-	-	-	-
• Metallic, secondary containment, unsure corrosion protection	-	-	16.4	-	-
• Metallic, secondary containment, no corrosion protection	-	-	-	-	-
• Metallic, no secondary containment, no corrosion protection	-	19.2	-	-	-
• Metallic, unsure secondary containment, unsure corrosion protection	-	-	-	-	-
• Unsure completely	19.2	-	-	-	-
<b>Pipework age</b>					
• > 30 years	7.4	7.4	-	-	-
• 20 - 30 years	-	-	-	5.6	-
• < 20 years	-	-	-	-	4
• Unsure	-	-	5.9	-	-
<b>Tank/pipework testing</b>					
• No evidence of testing in last 10 years	-	-	-	-	-
• 6-10 years	6.4	6.4	6.4	-	-
• 2-5 years	-	-	-	4.8	-
• < 2 years	-	-	-	-	3.2
• Unsure	-	-	-	-	-
<b>Leak detection system</b>					
• Manual tank dipping	-	-	-	-	-
• Static leak detection	5.2	-	5.2	-	-
• Monitoring wells	-	-	-	4.8	-
• Statistical leak detection	-	-	-	-	-
• Auto wetstock reconciliation	-	-	-	-	3.4
• Interstitial monitoring (tanks/pipes)	-	-	-	-	-
• Unsure	-	5.2	-	-	-
<b>Dispensing Hazards</b>					
<b>Pump type</b>					

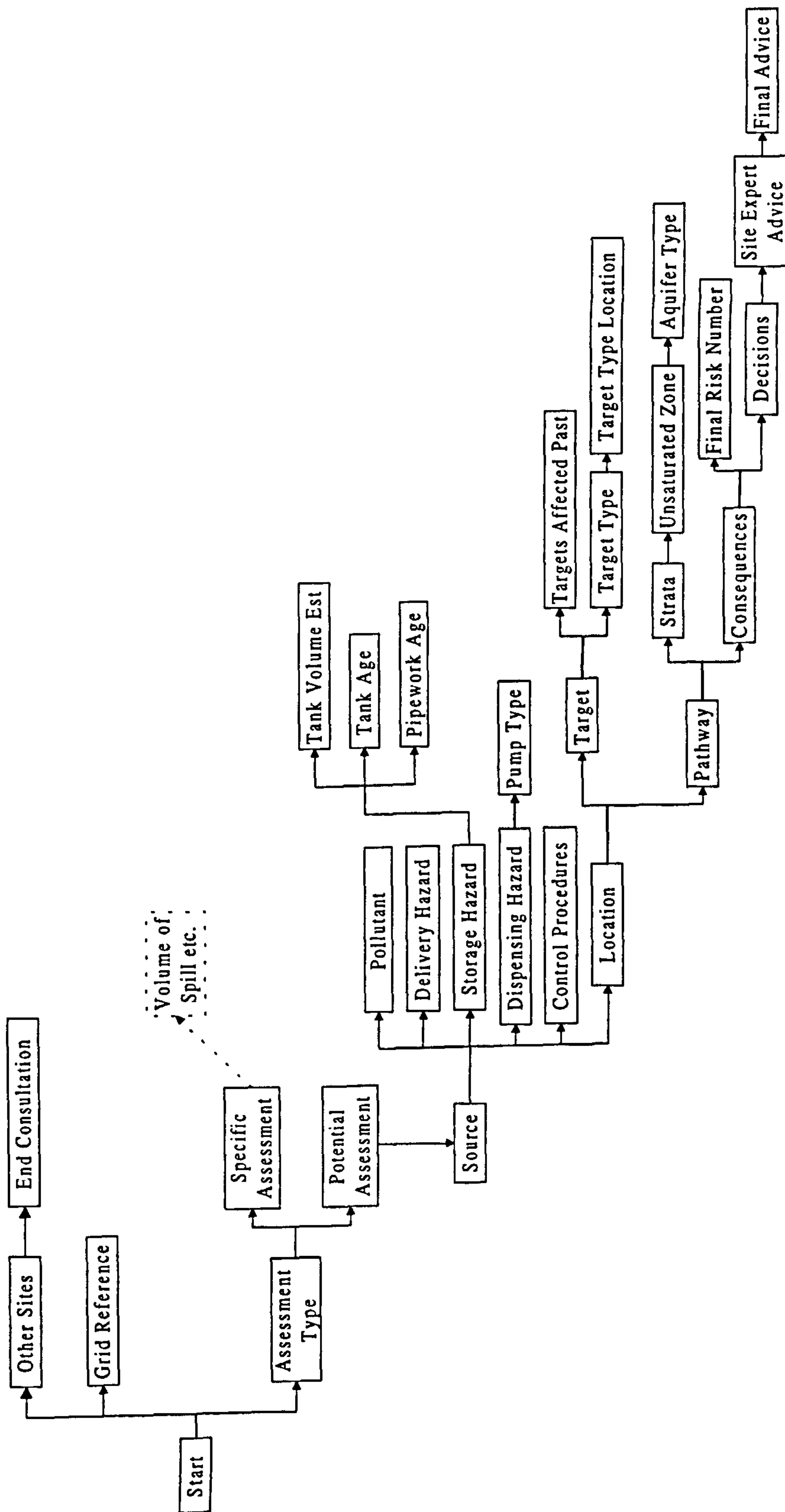
Table C.3 Contd.					
Parameters	Significance Categories				
	High	Medium-High	Medium	Medium-Low	Low
• BS 7117	-	-	3.2	3.2	3.2
• SFA 3002	-	-	-	-	-
• No standard	-	-	-	-	-
• Unsure - old site	4.8	-	-	-	-
• Unsure - new site	-	3.2	-	-	-
<b>Fuel distribution system</b>					
• Pressurised	6.8	6.8	-	-	-
• Suction/siphon	-	-	5.4	5.4	5.4
• Unsure	-	-	-	-	-
<b>Condition of pump island seals</b>					
• Good	-	-	-	-	-
• Poor	6.2	-	6.2	-	3
• Unsure	-	6.2	-	6.2	-
<b>Site Control Procedures</b>					
<b>Presence and adequacy of interceptor</b>					
• None	-	-	-	-	-
• Not adequate	8.2	8.2	8.2	8.2	-
• Adequate	-	-	-	-	4.2
• Unsure	-	-	-	-	-
<b>Drainage system drains to:</b>					
• Surface water	10	-	-	-	-
• Soakaway	-	8.2	8.2	8.2	-
• Sewer	-	-	-	-	5.2
• Uncertain	-	-	-	-	-
<b>Drainage system isolation</b>					
• Yes	-	-	-	-	4
• No	8.4	-	8.4	8.4	-
• Unsure	-	8.4	-	-	-
<b>Drainage system testing interval</b>					
• No evidence of testing in last 10 years	7.6	-	-	-	-
• 6-10 years	-	6.2	-	-	-
• 2-5 years	-	-	5.2	5.2	-
• Tested every 2 years or less	-	-	-	-	3.4
• Unsure	-	-	-	-	-
<b>Stage 4 - Exposure/Hazard Pathway</b>					
<b>Target Characterisation</b>					
<b>History of past incidents at the site</b>					
• None recorded	-	-	-	-	5
• Unsure if one occurred	-	-	-	-	-
• Other product, < 5000 litres	-	-	-	16	-
• Other product, unknown volume	-	-	-	-	-
• Diesel < 5000 litres	-	-	-	-	-
• Diesel, unknown volume	-	-	-	-	-
• Other products 5-10,000 litres	-	-	-	-	-
• Petrol < 5000 litres	-	-	19.6	-	-
• Petrol, unknown volume	-	19.6	-	-	-
• Unknown product, < 5000 litres	-	-	-	-	-
• Unknown product, unknown volume	-	-	-	-	-
• Diesel 5-10,000 litres	-	-	-	-	-
• Other products > 10,000 litres	-	-	-	-	-
• Petrol 5-10,000 litres	-	-	-	-	-



Table C.3 Contd.					
Parameters	Significance Categories				
	High	Medium-High	Medium	Medium-Low	Low
• Unknown product 5-10,000 litres	-	-	-	-	-
• Diesel > 10,000 litres	25.4	-	-	-	-
• Petrol > 10,000 litres	-	-	-	-	-
• Unknown product >10,000 litres	-	-	-	-	-
<b>Target impacted by previous incident</b>					
• Not affected	-	-	0	0	0
• Groundwater	-	25	-	-	-
• Surface water	-	-	-	-	-
• SSSI	-	-	-	-	-
• Industrial abstraction	-	-	-	-	-
• Agricultural abstraction	-	-	-	-	-
• Drinking water abstraction	29.6	-	-	-	-
• Unsure	-	-	-	-	-
<b>Identification of current target</b>					
• Groundwater > 51m	-	-	-	-	10
• Surface water 1.01km -10km	-	-	-	-	-
• Groundwater 26-50m	-	-	-	-	-
• SSSI 200-2km	-	-	-	-	-
• Groundwater 11-25m	-	-	-	-	-
• Surface water 501m -1km	-	-	-	-	-
• Ag/Ind abstraction 200m -2km	-	-	-	-	-
• Groundwater < 10m	-	-	-	19.3	-
• Surface water 50m -500m	-	-	19.8	-	-
• Drinking water 5.01km -10km	-	-	-	-	-
• SSSI < 200m	-	-	-	-	-
• Drinking water 2.01km -5km	-	-	-	-	-
• Ag/Ind < 200m	-	22.8	-	-	-
• Surface water < 50m	-	-	-	-	-
• Drinking water 200m -2km	25.6	-	-	-	-
• Drinking water < 200m	-	-	-	-	-
• Unsure	-	-	-	-	-
<b>Pathway Characterisation</b>					
<b>If identified target is a drinking water abstraction - SPZ designation</b>					
• SPZ I	12	-	-	-	-
• SPZ II	-	-	-	-	-
• SPZ III	-	-	-	-	-
• Unsure	-	9.9	-	-	-
<b>Strata underlying site</b>					
• Chalk	9.8	-	-	-	-
• Sandstone	-	8.6	8.6	8.6	-
• Clay	-	-	-	-	5
• Unsure	-	-	-	-	-
<b>Type of groundwater flow &amp; depth of unsaturated zone</b>					
• Intergranular > 51m	-	-	-	-	0
• Fissure > 51m	-	-	-	-	-
• Intergranular 26-50m	-	-	-	-	-
• Fissure 26-50m	-	-	-	14.4	-
• Intergranular 11-25m	-	-	14.8	-	-
• Fissure 11-25 m	-	15.8	-	-	-
• Intergranular < 10m	-	-	-	-	-

Table C.3 Contd.					
Parameters	Significance Categories				
	High	Medium-High	Medium	Medium-Low	Low
• Fissure < 10m	19.1	-	-	-	-
• Unsure	-	-	-	-	-
Aquifer permeability					
• High	10.4	10.4	-	-	-
• Medium	-	-	7.6	7.6	-
• Low	-	-	-	-	5.6
• Unsure	-	-	-	-	-
Hydraulic conductivity of unsaturated zone					
• Sands/gravels	10.4	10.4	-	-	-
• Sandstones	-	-	8.4	8.4	-
• Clays	-	-	-	-	6.2
• Unsure	-	-	-	-	-
Aquifer type					
• Major e.g. chalk	10.8	-	-	-	-
• Minor e.g. sand/gravels	-	8.2	-	-	-
• Non e.g. clays	-	-	4.8	4.8	4.8
• Unsure	-	-	-	-	-
<b>TOTALS</b>	<b>329.5</b>	<b>283.9</b>	<b>231.6</b>	<b>194.8</b>	<b>128.8</b>

C.4 HARRIS Section Tree



## C.5 HARRIS - Prototype Knowledge System Code

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section actual_assessment : 'investigation of actual incident '
do source_specific
section aquifer_type_est : ' estimating aquifer type underlying site'
advice 'You have indicated that you are not sure what type of aquifer, if any underlies 'site_name'. The relevant
Groundwater Vulnerability Map will tell you this information.'
if (aquifer_type_est='major') assign risknumber:=risknumber+10.8
if (aquifer_type_est='minor') assign risknumber:=risknumber+8.2
if (aquifer_type_est='non') assign risknumber:=risknumber+4.8
if (aquifer_type_est='still_unsure') assign risknumber:=risknumber+10.8
section assessment : 'assessment route '
if (assess='actual')
do actual_assessment
if (assess='potential')
do potential_assessment
section consequences : 'prediction of consequences '
advice 'HARRIS will now tell you what the risk number is that has been calculated for 'site_name' and will try and
give you some advice based on your answers to source, location and consequences sections, and some guidance as to
what you could do to reduce the risk that 'site_name' presents to groundwater. HARRIS can divide sites up into five
categories based on point-source severity classification in terms of significance to groundwater. These categories are
as follows:
    High significance
    Medium-high significance
    Medium significance
    Medium-low significance
    Low significance
These severity categories are based on those defined in the Environment Agency report - Groundwater pollution -
evaluation of the extent and character of groundwater pollution from point sources in England and Wales (de Henaut
et al, 1997).'
do final_risknumber
do decisions
section control_procedures : 'site control procedures '
advice 'The next few questions deal with overall site control procedures at 'site_name', such as interceptors, drainage
systems, site contingency plans.'
if (interceptor='none') assign risknumber:=risknumber+9.4
if (interceptor='interceptor_not_adequate') assign risknumber:=risknumber+8.2
if (interceptor='interceptor_adequate') assign risknumber:=risknumber+4.2
if (interceptor='unsure') assign risknumber:=risknumber+6.8
if (drainage='soakaway') assign risknumber:=risknumber+8.2
if (drainage='surface_water') assign risknumber:=risknumber+10
if (drainage='sewer') assign risknumber:=risknumber+5.2
if (drainage='unsure') assign risknumber:=risknumber+7.6
if (drainage_isolation1='yes') assign risknumber:=risknumber+4
if (drainage_isolation1='no') assign risknumber:=risknumber+8.4
if (drainage_isolation1='unsure') assign risknumber:=risknumber+8.4
if (drainage_test='more_ten_years') assign risknumber:=risknumber+7.6
if (drainage_test='ten_years') assign risknumber:=risknumber+6.2
if (drainage_test='five_years') assign risknumber:=risknumber+5.2
if (drainage_test='one_year') assign risknumber:=risknumber+3.4
if (drainage_test='unsure') assign risknumber:=risknumber+5
section decisions : 'decisions to be made '
advice 'HARRIS has now helped you to classify 'site_name' as of 'severity1' significance in terms of point source
severity of groundwater pollution. So what can be done to perhaps reduce this potential impact on groundwater
presented by 'site_name' ? The next screen will give you some advice. '
if (assess='actual') do spill_expertadvice
if (assess='potential') do site_expertadvice
/*chain 'end.kb'*/
section delivery_hazard : 'identification of hazards/hazard pathways during delivery '
advice 'The next few questions deal with delivery hazards at 'site_name'.'
picture 'fillpoint'
if (fill_point='direct_fill') assign risknumber:=risknumber+6.6
if (fill_point='off_set_fill_aboveground_bund') assign risknumber:=risknumber+3.8
if (fill_point='off_set_fill_aboveground') assign risknumber:=risknumber+6.4
if (fill_point='off_set_fill_belowground_containment') assign risknumber:=risknumber+4
if (fill_point='off_set_fill_belowground') assign risknumber:=risknumber+6.2
if (fill_point='not_sure') assign risknumber:=risknumber+6
if (o_p_d='yes') assign risknumber:=risknumber+3.2

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if (o_p_d='no') assign risknumber:=risknumber+6
if (o_p_d='unsure') assign risknumber:=risknumber+3.2
if (concrete_pad='yes') assign risknumber:=risknumber+4.8
if not (concrete_pad='no') assign risknumber:=risknumber+8.2
if not (concrete_pad='unsure') assign risknumber:=risknumber+6.5
section dispensing_hazard : 'Identification of hazards/hazard pathways during dispensing operations '
advice 'The next questions relate to dispensing of fuel at 'site_name'.'
picture 'pump'
if (pipe_delivery_system='suction') assign risknumber:=risknumber+5.4
if (pipe_delivery_system='pressure') assign risknumber:=risknumber+6.8
if (pipe_delivery_system='unsure') assign risknumber:=risknumber+5.4
if (pump='pump_no_standard') assign risknumber:=risknumber+6.2
if (pump='pump_3002') assign risknumber:=risknumber+4.8
if (pump='pump_7117') assign risknumber:=risknumber+3.2
if (pump='not_sure') do pump_type
if (pump_island_seal='yes') assign risknumber:=risknumber+3
if (pump_island_seal='no') assign risknumber:=risknumber+6.2
if (pump_island_seal='unsure') assign risknumber:=risknumber+6.2
section end_consultation : 'the end '
advice 'Unfortunately HARRIS is designed to focus on retail petroleum sites at the moment, so HARRIS is not yet designed to help you with your particular site type or activity so this is : THE END. Try looking at petrol stations instead'
chain 'end-kb'
section final_advice : 'last piece of advice instead of end kb '
advice 'You have reached the end of this consultation with HARRIS. Thank you for your time. Here are a few useful contacts: National Groundwater and Contaminated Land Centre, Environment Agency, Olton Court, Solihull - 0121 7242324. Institute of Petroleum, New Cavendish Street, London.'
section final_risknumber : 'calculation of final risknumber '
advice 'The site risk number has been calculated as 'risknumber'
A risk number of 'risknumber' puts 'site_name' into the 'severity1' significance category in terms of risk to groundwater. '
section grid_ref : 'identify position of the site '
advice 'Site location will now be recorded as 'grid'. This is only an approximate location and is just used for recording and reporting purposes. '
section location : 'location of pollution '
advice 'This section helps you evaluate the location of the pollution i.e., pathway and target terms, what any pollutant may affect and how it might get there.'
do targets
do pathway
section other_sites : 'everything other than petrol stations '
do end_consultation
section pathway : 'pathway characteristics '
advice 'Moving on to questions on pathway'
if (target_type='drinking_abs') and (gpz='I') assign risknumber:=risknumber+12
if (target_type='drinking_abs') and (gpz='II') assign risknumber:=risknumber+9.8
if (target_type='drinking_abs') and (gpz='III') assign risknumber:=risknumber+7.8
if (target_type='drinking_abs') and (gpz='none') assign risknumber:=risknumber+9.9
do strata_unsaturated_zone
do consequences
section pipework_age : 'establish age of pipework '
if (pipework_age='more_than_thirty') assign risknumber:=risknumber+7.4
if (pipework_age='twenty_to_thirty') assign risknumber:=risknumber+5.6
if (pipework_age='less_than_twenty') assign risknumber:=risknumber+4
if (pipework_age='unsure') assign risknumber:=risknumber+5.9
section pollutant : 'potential pollutant type '
advice 'Petroleum in the UK is now sold in three different grades, leaded (red pipes), unleaded (green pipes) and super unleaded (blue pipes). Petrol forms about 80% of retail fuel sales in the UK. It is more volatile and more soluble than diesel and will migrate faster through the soil. The vast majority of sites in the UK sell more than one product. So petrol and diesel are likely to be present on site, over 95% sell both. Diesel or DERV forms about 20% of retail sales at petrol filling stations in the UK. Diesel fuel is less volatile than petrol and less soluble. It will migrate much more slowly than petrol but it will migrate.'
if (diesel1='yes') assign risknumber:=risknumber+11.6
if (diesel1='no') assign risknumber:=risknumber+risknumber
if (petrol1='yes') assign risknumber:=risknumber+12.2
if (petrol1='no') assign risknumber:=risknumber+risknumber
if (diesel1='unsure') assign risknumber:=risknumber+11.6
if (petrol1='unsure') assign risknumber:=risknumber+12.2
if (type_others='mineral_oil') assign risknumber:=risknumber+8.6

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if (type\_others='fuel\_oil') assign risknumber:=risknumber+8.6  
 if (type\_others='paraffin') assign risknumber:=risknumber+8.6  
 if (type\_others='none') assign risknumber:=risknumber  
 if (type\_others='unsure') assign risknumber:=risknumber  
**section potential\_assessment : 'do whole site assessment '**  
 do source  
**section pump\_type : 'estimating pump type on site '**  
 advice 'You have indicated that you do not know what type of pump is present on site. On modern sites all pumps should be to BS 7117 and will all be of a similar type. The site manager and site plans should also be able to help. Each pump also has a small plate attached to it which states to what standard it has been designed to. The chances are that on a modern site, pumps will be designed to a recognised standard.'  
 if (pump\_type\_est='plate\_BS7117') assign risknumber:=risknumber+3.2  
 if (pump\_type\_est='plate\_not\_BS7117') assign risknumber:=risknumber+4.8  
 if (pump\_type\_est='no\_plate') assign risknumber:=risknumber+6.2  
 if (pump\_type\_est='modern\_site') assign risknumber:=risknumber+3.2  
 if (pump\_type\_est='old\_site') assign risknumber:=risknumber+4.8  
**section site\_expertadvice : 'HARRIS finds what risknumber is and gives advice '**  
 advice 'You have used HARRIS to assess the potential of 'site\_name' to pollute groundwater. HARRIS has calculated a risk number of 'risknumber' and the site has been categorised as a 'severity1' significance site in terms of risk to groundwater. The following advice is set out along the lines of source-pathway-target, but as this an already existing site there is not much you can do to reduce the risk to groundwater by changing the pathway and target parameters, so most of the advice is focused on the site itself. Advice for possible action to reduce the risk to groundwater by altering site conditions is split into:  
 Delivery of fuel, Dispensing of fuel and Storage of fuel.'  
 if fill\_point='off\_set\_fill\_aboveground' and (o\_p\_d='no' or o\_p\_d='unsure') and (concrete\_pad='no' or concrete\_pad='unsure')  
 advice 'Delivery of fuel at site\_name.  
 Even though 'site\_name' has off-set fill-points for tankers to delivery their fuel and they are aboveground, so easily maintained and can be checked for leaks, the area is not bunded. This means that any spills that occur during delivery could possibly escape from the site and not be dealt with by the site drainage system. A simple bund built of hydrocarbon resistant material could prevent this. You indicated to HARRIS that 'site\_name' does not have over-fill protection devices fitted to the fill-point or your are not sure if it does. These devices stop a tank being over-filled and a spill occurring. Most modern sites do have these devices fitted in some form - check with the site manager. They should be fitted on all tanks. The condition of the concrete pad where tanker deliveries occur can affect how a leak or spill will impact on groundwater. During this session you indicated that the forecourt of 'site\_name' is not in good condition or you were not sure if it was. Cracked and damaged forecourts are much more likely at older less well maintained sites and as they may provide a direct pathway for fuel to enter the soil should be repaired as soon as possible and all joints sealed with hydrocarbon resistant material.'  
 if fill\_point='off\_set\_fill\_belowground' and (o\_p\_d='no' or o\_p\_d='unsure')  
 advice 'Delivery at site\_name.  
 Even though 'site\_name' has off-set fill-points for tankers to deliver their fuel, they are underground. This is good from the point of view that they are protected from vehicles crashing into them etc. but at 'site\_name' there is no secondary containment. This means that if there is a leak that fuel will be able to escape from the site and enter the soil/unsaturated zone directly. Getting some secondary containment such as a impermeable chamber put around the fill point would reduce the chances of any fuel escaping. You indicated to HARRIS that 'site\_name' does not have over-fill protection devices fitted to the fill-point or your are not sure if it does. These devices stop a tank being over-filled and a spill occurring. Most modern sites do have these devices fitted in some form - check with the site manager. They should be fitted on all tanks.'  
 if fill\_point='direct\_fill' and (o\_p\_d='no' or o\_p\_d='unsure')  
 advice 'Delivery at site\_name.  
 You indicated that 'site\_name' has direct tank fills. Direct tank fills are not all that common at retail petroleum sites. Direct fills can allow the tank to become overfilled and spills can escape easily. To improve the situation an off-set fill should be installed, bunded if its aboveground or with secondary containment if below ground. You indicated to HARRIS that 'site\_name' does not have over-fill protection devices fitted to the fill-point or your are not sure if it does. These devices stop a tank being over-filled and a spill occurring. Most modern sites do have these devices fitted in some form - check with the site manager. They should be fitted on all tanks.'  
 if fill\_point='not\_sure' and (o\_p\_d='no' or o\_p\_d='unsure') and (concrete\_pad='no' or concrete\_pad='unsure')  
 advice 'Delivery at site\_name.  
 You are not sure what type of fill point exists at 'site\_name'. On a retail site it will almost certainly be an off-set fill and HARRIS has taken that into account in categorising 'site\_name'. To make a more accurate assessment carry out a site visit and run through a session with HARRIS again. You indicated to HARRIS that 'site\_name' does not have over-fill protection devices fitted to the fill-point or your are not sure if it does. These devices stop a tank being over-filled and a spill occurring. Most modern sites do have these devices fitted in some form - check with the site manager. They should be fitted on all tanks. The condition of the concrete pad where tanker deliveries occur can affect how a leak or spill will impact on groundwater. During this session you indicated that the forecourt of 'site\_name' is not in good condition or you were not sure if it was. Cracked and damaged forecourts are much more likely at older less well maintained sites and as they may provide a direct pathway for fuel to enter the soil should be repaired as soon as possible and all joints sealed with hydrocarbon resistant material.'

```

if (tank_construction='single_steel' or tank_construction='unsure')
advice 'site_name' has tanks made of single-skinned steel (or you are not sure what they are made of, single skinned
steel is most likely). Single skinned steel tanks are vulnerable to corrosion.'
do final_advice
section source : 'evaluate source term '
advice 'The next set of questions ask about the site, which is the potential source of pollution. Questions are based on
the main site activities, such as:
1) Delivery of fuel (from tanker to site)
2) Storage of fuel (tanks and associated pipework)
3) Dispensing of fuel (from pumps into cars etc)'
do pollutant
do delivery_hazard
do storage_hazard
do dispensing_hazard
do control_procedures
do location
section start : 'evaluate site type '
advice 'Hello and welcome to this consultation session with the HARRIS system. Use the scroll bar on the right to
read the rest of this introduction. If you want to exit HARRIS, just use the Stop button on the left. HARRIS stands
for Hydrocarbon and Risk Related Information System - it focuses on petroleum hydrocarbons such as petrol and
diesel and their impact on groundwater. The Source-Pathway-Target model has been used and a risk management
approach applied to that model. There are 8 stages to the complete process, although HARRIS focuses on stage 1 to
6. The stages are shown here:
    Stage 1 - Identification of work areas or site
    Stage 2 - Analysis of activities on site
    Stage 3 - Identification of hazards
    Stage 4 - Exposure/Hazard pathway
    Stage 5 - Prediction of consequences
    Stage 6 - Completion of risk assessment process
    Stage 7 - Risk acceptability
    Stage 8 - Identification of possible actions
            - Completion of the risk management process
This is not a "black-box" program, and although you will have to input some data, the system will ask you questions
and usually give you a list of options to choose from. If you are unsure of what information you are looking at the
"Explain" button will give you some guidance. As you move through the system, a "risk number" for your site will be
calculated. This is a number computed by HARRIS that can be used to compare sites and prioritise them in terms of
risk to groundwater. The risk number is calculated using expert judgement contained in HARRIS so you do not
have to calculate a number yourself. This is a semi-quantitative risk assessment program so large amounts of
numerical data are not required. HARRIS is a decision-support system, emphasis on the support, it will help you
make your own decisions, it will not make them for you. It will help you think of the right questions to ask yourself
when out on site without computer support and encourage decision-making in a risk-based way - it is not a magic box
! A site visit is not required but is recommended. The "Explain" button will give you some help if you need it, the
"Why" button is best avoided but have a look anyway if you want! Please click on the OK button to your left to
continue'
if (site_type='petrol_filling_station') assign risknumber:=10
if not (site_type='petrol_filling_station') do other_sites
assign base_risk_number:=risknumber
advice 'You have chosen a petrol filling station as the site under investigation during this session. In terms of risk to
groundwater, a retail petrol station has the minimum "risk number" of 'base_risk_number'. This is based on expert
judgement and takes into account a whole variety of other point-sources. The site minimum or base risk number and
can not be reduced by engineering the site etc.'
do grid_ref
do assessment
section storage_hazard : 'storage hazards detailed'
advice 'The next set of questions are about storage hazards on site, type of tank etc.'
picture 'pipework'
if (tank_vol='hundred_thousand') assign risknumber:=risknumber+5.6
if (tank_vol='fifty_hundred_thousand') assign risknumber:=risknumber+5.2
if (tank_vol='less_fifty') assign risknumber:=risknumber+4.8
if (tank_vol='unsure') do tank_vol_estimate
if (tank_construction='single_steel') and (cathodic_tank='yes') assign risknumber:=risknumber+7.4
if (tank_construction='single_steel') and (cathodic_tank='no') assign risknumber:=risknumber+9
if (tank_construction='single_steel') and (cathodic_tank='unsure') assign risknumber:=risknumber+9
if (tank_construction='double_steel') and (cathodic_tank='yes') assign risknumber:=risknumber+4.6
if (tank_construction='double_steel') and (cathodic_tank='no') assign risknumber:=risknumber+6.2
if (tank_construction='double_steel') and (cathodic_tank='unsure') assign risknumber:=risknumber+6.2
if (tank_construction='grp') assign risknumber:=risknumber+4.4
if (tank_construction='steel_grp') assign risknumber:=risknumber+2

```

```

if (tank_construction='unsure') assign risknumber:=risknumber+9
if (tank_age1='yes') do tank_age
if (tank_age1='no') assign risknumber:=risknumber+7
if (tank_age1='unsure') assign risknumber:=risknumber+7
if (pipe_construction='single') and (cathodic_pipe1='yes') assign risknumber:=risknumber+16
if (pipe_construction='single') and (cathodic_pipe1='no') assign risknumber:=risknumber+19.2
if (pipe_construction='single') and (cathodic_pipe1='unsure') assign risknumber:=risknumber+19.2
if (pipe_construction='double') and (cathodic_pipe1='yes') assign risknumber:=risknumber+13.2
if (pipe_construction='double') and (cathodic_pipe1='no') assign risknumber:=risknumber+16.4
if (pipe_construction='double') and (cathodic_pipe1='unsure') assign risknumber:=risknumber+16.4
if (pipe_construction='non-metallic') assign risknumber:=risknumber+10
if (pipe_construction='non_metallic_contained') assign risknumber:=risknumber+7.2
if (pipe_construction='non_metallic_contained_unsure') assign risknumber:=risknumber+10
if (pipe_construction='unsure') assign risknumber:=risknumber+19.2
if (pipework_age1='yes') do pipework_age
if (pipework_age1='no') assign risknumber:=risknumber+5.9
if (pipework_age1='unsure') assign risknumber:=risknumber+5.9
if (leak_detection='manual') assign risknumber:=risknumber+7
if (leak_detection='wells') assign risknumber:=risknumber+4.8
if (leak_detection='static') assign risknumber:=risknumber+5.2
if (leak_detection='statistical') assign risknumber:=risknumber+4
if (leak_detection='automatic') assign risknumber:=risknumber+3.4
if (leak_detection='interstitial_pipe_tank') assign risknumber:=risknumber+3.4
if (leak_detection='unsure') assign risknumber:=risknumber+5.2
if (tank_test='more_ten_years') assign risknumber:=risknumber+8
if (tank_test='ten_years') assign risknumber:=risknumber+6.4
if (tank_test='five_years') assign risknumber:=risknumber+4.8
if (tank_test='one_year') assign risknumber:=risknumber+3.2
if (tank_test='unsure') assign risknumber:=risknumber+5.6
section strata_unsaturated_zone : 'strata type and unsaturated zone characteristics '
if (strata_type='clay') assign risknumber:=risknumber+5
if (strata_type='sandstone') assign risknumber:=risknumber+8.6
if (strata_type='limestone') assign risknumber:=risknumber+9.8
if (strata_type='unsure') assign risknumber:=risknumber+7.4
if (flow_type='fissure') and (depth_unsaturated_zone <=10) assign risknumber:=risknumber+19.1
if (flow_type='intergranular') and (depth_unsaturated_zone <=10) assign risknumber:=risknumber+17.7
if (flow_type='fissure') and (depth_unsaturated_zone > 10 and depth_unsaturated_zone <=25) assign
risknumber:=risknumber+15.8
if (flow_type='intergranular') and (depth_unsaturated_zone > 10 and depth_unsaturated_zone <=25) assign
risknumber:=risknumber+14.8
if (flow_type='fissure') and (depth_unsaturated_zone > 25 and depth_unsaturated_zone <=50) assign
risknumber:=risknumber+14.4
if (flow_type='intergranular') and (depth_unsaturated_zone > 25 and depth_unsaturated_zone <=50) assign
risknumber:=risknumber+13.2
if (flow_type='fissure') and (depth_unsaturated_zone > 50) assign risknumber:=risknumber+8.4
if (flow_type='intergranular') and (depth_unsaturated_zone > 50) assign risknumber:=risknumber
if (flow_type='unsure') and (depth_unsaturated_zone <=10) assign risknumber:=risknumber+11
if (flow_type='unsure') and (depth_unsaturated_zone >10 and depth_unsaturated_zone <=25) assign
risknumber:=risknumber+19.1
if (flow_type='unsure') and (depth_unsaturated_zone >25 and depth_unsaturated_zone <=50) assign
risknumber:=risknumber+19.1
if (flow_type='unsure') and (depth_unsaturated_zone >50) assign risknumber:=risknumber+19.1
if (permeability_aquifer='high') assign risknumber:=risknumber+10.4
if (permeability_aquifer='medium') assign risknumber:=risknumber+7.6
if (permeability_aquifer='low') assign risknumber:=risknumber+5.6
if (permeability_aquifer='unsure') assign risknumber:=risknumber+10.4
if (conductivity_unsaturated='sands') assign risknumber:=risknumber+10.4
if (conductivity_unsaturated='sandstone') assign risknumber:=risknumber+8.4
if (conductivity_unsaturated='clay') assign risknumber:=risknumber+6.2
if (conductivity_unsaturated='unsure') assign risknumber:=risknumber+10.4
if (aquifer='major') assign risknumber:=risknumber+10.8
if (aquifer='minor') assign risknumber:=risknumber+8.2
if (aquifer='non') assign risknumber:=risknumber+4.8
if (aquifer='chalk') assign risknumber:=risknumber+10.8
if (aquifer='sandstone') assign risknumber:=risknumber+10.8
if (aquifer='limestone') assign risknumber:=risknumber+10.8
if (aquifer='greensand') assign risknumber:=risknumber+10.8
if (aquifer='grit') assign risknumber:=risknumber+8.2

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if (aquifer='alluvium') assign risknumber:=risknumber+8.2
if (aquifer='coal') assign risknumber:=risknumber+8.2
if (aquifer='sand') assign risknumber:=risknumber+8.2
if (aquifer='marls') assign risknumber:=risknumber+4.8
if (aquifer='mud') assign risknumber:=risknumber+4.8
if (aquifer='clay') assign risknumber:=risknumber+4.8
if (aquifer='unsure') do aquifer_type_est
section tank_age : ' establish tank_age '
if (tank_age='more_than_thirty') assign risknumber:=risknumber+8.8
if (tank_age='twenty_to_thirty') assign risknumber:=risknumber+7
if (tank_age='less_than_twenty') assign risknumber:=risknumber+5.2
if (tank_age='unsure') assign risknumber:=risknumber+7
section tank_vol_estimate : 'estimating operational tank volume '
advice 'As you are not sure what the operational tank volume of 'site_name' is, the following question will help you
estimate what the volume may be for the purposes of this assessment only'
if (tank_vol_est='motorway') assign risknumber:=risknumber+5.6
if (tank_vol_est='town') assign risknumber:=risknumber+5.2
if (tank_vol_est='rural') assign risknumber:=risknumber+4.8
section target_affected_past : 'target affected in past '
if (target_type_affected='drinking_abs') assign risknumber:=risknumber+29.6
if (target_type_affected='agi_abs') assign risknumber:=risknumber+26.4
if (target_type_affected='ind_abs') assign risknumber:=risknumber+26.4
if (target_type_affected='nature') assign risknumber:=risknumber+25.4
if (target_type_affected='water') assign risknumber:=risknumber+25.4
if (target_type_affected='gw') assign risknumber:=risknumber+25
if (target_type_affected='unsure') assign risknumber:=risknumber+29.6
section target_type : 'type of target affected now '
do target_type_location
section target_type_location : 'identification of target type and location from source '
if (target_type='drinking_abs') and (target_location < 200) assign risknumber:=risknumber+28.6
if (target_type='drinking_abs') and (target_location >=200 and target_location <= 2000) assign
risknumber:=risknumber+25.6
if (target_type='drinking_abs') and (target_location > 2000 and target_location <= 5000) assign
risknumber:=risknumber+22.2
if (target_type='drinking_abs') and (target_location > 5000) assign risknumber:=risknumber+20.6
if (target_type='agi_abs') and (target_location <200) assign risknumber:=risknumber+22.8
if (target_type='agi_abs') and (target_location >=200) assign risknumber:=risknumber+18.2
if (target_type='ind_abs') and (target_location <200) assign risknumber:=risknumber+22.8
if (target_type='ind_abs') and (target_location >=200) assign risknumber:=risknumber+18.2
if (target_type='nature') and (target_location <200) assign risknumber:=risknumber+20.8
if (target_type='nature') and (target_location >=200) assign risknumber:=risknumber+16.2
if (target_type='water') and (target_location <50) assign risknumber:=risknumber+22.8
if (target_type='water') and (target_location >= 50 and target_location <= 500) assign risknumber:=risknumber+19.8
if (target_type='water') and (target_location > 500 and target_location <= 1000) assign risknumber:=risknumber+17.8
if (target_type='water') and (target_location >1000) assign risknumber:=risknumber+15.8
if (target_type='gw') and (depth_unsaturated_zone <10) assign risknumber:=risknumber+19.3
if (target_type='gw') and (depth_unsaturated_zone >=10 and depth_unsaturated_zone <=25) assign
risknumber:=risknumber+17.2
if (target_type='gw') and (depth_unsaturated_zone >25 and depth_unsaturated_zone <=50) assign
risknumber:=risknumber+16
if (target_type='gw') and (depth_unsaturated_zone >50) assign risknumber:=risknumber+10
if (target_type='unsure') assign risknumber:=risknumber+28.6
/*score is a function of what the target is and how far away it is
except when its just groundwater, then its a function of depth of unsaturated zone
if no target identified, groundwater itself taken as target*/
section targets : 'target identification '
advice 'Targets first - the following questions deal with potential targets of any groundwater pollution and whether
they have been affected. Groundwater itself could be a potential target plus drinking water abstractions etc. are
targets. It is not only the type of potential target which is important but how far away it is from 'site_name', so there
are two main parts to this part of the assessment.'
if (leaked_before='yes') and (pollutant_type1='petrol') and (leak_before_vol='ten_thousand') assign
risknumber:=risknumber+26
if (leaked_before='yes') and (pollutant_type1='petrol') and (leak_before_vol='five_ten_thousand') assign
risknumber:=risknumber+22.8
if (leaked_before='yes') and (pollutant_type1='petrol') and (leak_before_vol='less_five_thousand') assign
risknumber:=risknumber+19.6
if (leaked_before='yes') and (pollutant_type1='petrol') and (leak_before_vol='unsure'). assign
risknumber:=risknumber+19.6

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if (leaked_before='yes') and (pollutant_type1='diesel') and (leak_before_vol='ten_thousand') assign
risknumber:=risknumber+25.4
if (leaked_before='yes') and (pollutant_type1='diesel') and (leak_before_vol='five_ten_thousand') assign
risknumber:=risknumber+22.2
if (leaked_before='yes') and (pollutant_type1='diesel') and (leak_before_vol='less_five_thousand') assign
risknumber:=risknumber+19
if (leaked_before='yes') and (pollutant_type1='diesel') and (leak_before_vol='unsure') assign
risknumber:=risknumber+19
if (leaked_before='yes') and (pollutant_type1='other') and (leak_before_vol='ten_thousand') assign
risknumber:=risknumber+22.4
if (leaked_before='yes') and (pollutant_type1='other') and (leak_before_vol='five_ten_thousand') assign
risknumber:=risknumber+19.2
if (leaked_before='yes') and (pollutant_type1='other') and (leak_before_vol='less_five_thousand') assign
risknumber:=risknumber+16
if (leaked_before='yes') and (pollutant_type1='other') and (leak_before_vol='unsure') assign
risknumber:=risknumber+16
if (leaked_before='yes') and (pollutant_type1='unsure') and (leak_before_vol='ten_thousand') assign
risknumber:=risknumber+26
if (leaked_before='yes') and (pollutant_type1='unsure') and (leak_before_vol='five_ten_thousand') assign
risknumber:=risknumber+22.8
if (leaked_before='yes') and (pollutant_type1='unsure') and (leak_before_vol='less_five_thousand') assign
risknumber:=risknumber+19.6
if (leaked_before='yes') and (pollutant_type1='unsure') and (leak_before_vol='unsure') assign
risknumber:=risknumber+19.6
if (leaked_before='no') assign risknumber:=risknumber+5
if (leaked_before='unsure') assign risknumber:=risknumber+5
if (target_affected='yes') do target_affected_past
if (target_affected='no') assign risknumber:=risknumber
if (target_affected='unsure') assign risknumber:=risknumber+5
do target_type

```

**parameter aquifer : 'type of aquifer '**

type category

explanation 'This question can be answered directly if you know exactly what sort of aquifer underlies the site, or if you already know it is a major aquifer for example. The type of aquifer which underlies the site is obviously very important in terms of groundwater protection. A major aquifer requires a higher level of protection in terms of drinking water etc. than a non aquifer. Although a non aquifer could be important in providing groundwater for river base flow etc. If you are not sure what type of aquifer, if any underlies 'site\_name'. The relevant geology map will tell you this information or look at the Groundwater Vulnerability maps.'

options

```

chalk - 'Chalk ',
sandstone - 'Sandstones e.g., Sherwood Sandstone',
limestone - 'Limestones e.g., Carboniferous Limestone',
greensand - 'Greensands e.g., Upper Greensand',
alluvium - 'Alluvium',
sand - 'Sand/gravel',
coal - 'Coal measures',
grit - 'Millstone grit ',
clay - 'Clays e.g., Jurassic clays',
mud - 'Mudstone e.g., Mercia Mudstone group',
marls - 'Marls e.g., Permian marls ',
major - 'Known major aquifer',
minor - 'Known minor aquifer',
non - 'Known non-aquifer',
unsure - 'Not really sure' .

```

question 'What sort of aquifer is below 'site\_name' ?'

**parameter aquifer\_type\_est : 'estimating the underlying aquifer if any '**

type category

explanation 'You have indicated that you are not sure of the aquifer type that underlies 'site\_name' . The type of aquifer that the site overlies (if any) is very important in terms of assessing the risk to groundwater from any leaks etc. Find the relevant Groundwater Vulnerability Map for the area where 'site\_name' is located, aquifer type will be indicated on the map. If you can not get access to the relevant Vulnerability map this assessment will assume the worst case scenario, which is that the site overlies a major aquifer.'

options

```

major - 'Major aquifer ',
minor - 'Minor aquifer ',
non - 'Non-aquifer '
still_unsure - 'Still not sure' .

```

question 'Identify which type of aquifer lies below 'site\_name' ?'

**parameter aquifer\_types : 'designation of aquifer '**

## type category

explanation 'The type of aquifer that 'site\_name' overlies (if any) is very important in terms of assessing the risk to groundwater from any leaks etc. '

## options

- major - 'Major aquifer ',
- minor - 'Minor aquifer ',
- non - 'Non-aquifer '
- unsure - 'Not really sure' .

question 'Which type of aquifer has been designated by the Environment Agency as underlying 'site\_name' ? '

**parameter assess : 'assessment type '**

## type category

explanation 'HARRIS is designed to allow you to choose what type of assessment you want to carry out. If you are investigating a specific incident at a site, such as a spill, you need to carry out a specific incident assessment. In this case only the risk to groundwater from the particular incident at your site will be looked at. If you are looking at a site to assess its potential to impact on groundwater or are trying to compare a selection of sites to prioritise them for action, you need to carry out a whole site assessment. '

## options

- potential - 'Potential of site to impact on groundwater',
- actual - 'Specific incident assessment (spill/leak has occurred) '.

question 'What are you trying to assess ? '

**parameter base\_risk\_number : 'the base risk number is based on site type '**

## type number

**parameter cathodic\_pipe1 : 'find out if pipes have cathodic protection '**

## type category

explanation 'Like steel tanks, steel pipes can be protected from corrosion by coatings (bitumen and/or epoxy resins) or by using cathodic protection. Cathodic protection is preferential and there are two types: Sacrificial Anodes - metals such as zinc or magnesium connected to the tank by electric cables, these metals will corrode preferentially compared to the steel tank. Impressed Current - uses a DC electrical current to polarise the tank. '

## options

- yes - 'Yes ',
- no - 'No ',
- unsure - 'Not sure '.

question 'Do the metallic pipes have corrosion protection e.g. cathodic protection ? '

**parameter cathodic\_tank : 'cathodic protection on tanks '**

## type category

explanation 'Steel tanks can be protected from corrosion by tank coatings (bitumen and/or epoxy resins) or by using cathodic protection. Cathodic protection is preferential and there are two types: Sacrificial Anodes - metals such as zinc or magnesium connected to the tank by electric cables, these metals will corrode preferentially compared to the steel tank. Impressed Current - uses a DC electrical current to polarise the tank. '

## options

- yes - 'Yes ',
- no - 'No ',
- unsure - 'Not sure '.

question 'Do the tanks have corrosion protection such as cathodic protection installed ? '

**parameter concrete\_pad : 'condition of concrete pad '**

## type category

explanation 'Condition of the concrete pad area where tankers deliver loads of petroleum should be in good condition. Areas of cracking or unsealed concrete joints could allow any spillages to penetrate below the concrete pad and escape the site drainage system. Spillages could progress directly into surrounding soil and hence reach the water table.'

## options

- yes - 'Yes ',
- no - 'No ',
- unsure - 'Not sure '.

question 'Is the condition of the concrete pad where the tankers deliver their loads good, with no cracked areas or unsealed joints ? '

**parameter conductivity\_unsaturated : 'hydraulic conductivity of unsaturated zone '**

## type category

explanation 'Hydraulic conductivity is a more accurate way to describe permeability. It depends not just on the medium (e.g. clays or sands/gravels) but on the type of fluid passing through it e.g. water or oil. The viscosity (kinematic viscosity) of the fluid affects the hydraulic conductivity - the lower the kinematic viscosity, the higher the hydraulic conductivity. However in terms of hydrology the viscosity of water is relatively constant from one aquifer to another. However, when looking at other types of fluid, viscosity will vary e.g. oil-bearing strata, then a measure called intrinsic permeability is used. In hydrogeology when one rock is said to be more permeable than another, this is strictly speaking intrinsic permeability and not hydraulic conductivity but as the variation in viscosity of water is so small this distinction is ignored. Rocks and the unsaturated zone material are unfortunately not uniform in nature and will almost certainly vary from place to place - they are heterogeneous. Therefore the permeabilities also vary. So

any assumptions made by HARRIS are on a gross scale and can only be used as a guide for the purpose of this assessment only.'

options

sands - 'More than 10-4 cm/sec (sands/gravels) ',

sandstone - '10-4 to 10-6 cm/sec (sandstones) ',

clay - 'Less than 10-6 cm/sec (clays) ',

unsure - 'Not really sure ',

none - 'No unsaturated zone present'.

question 'What is the hydraulic conductivity of the unsaturated zone '

parameter **depth\_unsaturated\_zone** : 'establish depth of unsaturated zone '

type number

explanation 'Depth of the unsaturated zone is important when assessing risk to groundwater from petrol filling stations. The depth of the unsaturated zone is the depth to the water table. If there is no unsaturated zone present enter a zero. '

/\* range field \*/

question 'What is the depth of the unsaturated zone (in metres) at 'site\_name' ? '

parameter **diesel1** : 'establish whether diesel on site '

type category

explanation 'Diesel or DERV forms about 20% of retail sales at petrol filling stations in the UK but is sold at over 95% of sites. Look at the dispensing pumps to check what products are being sold from the site '

options

yes - 'Yes ',

no - 'No ',

unsure - 'Not really sure '.

question 'Does 'site\_name' store diesel on site ? '

parameter **drainage** : 'drainage system flows to where '

type category

explanation 'A site drainage system present at a site (even if there is an interceptor) may still present a risk to groundwater in terms of allowing any spilled or leaked fuel to enter that drainage system and not be contained at the site. Drainage systems can flow to soakaways, surface water bodies or sewer.'

options

soakaway - 'Drains to soakaway ',

surface\_water - 'Drains to surface water ',

sewer - 'Drains to sewer',

unsure - 'Not really sure '.

question 'Where does the site drainage system, including any interceptors, drain to ? '

parameter **drainage\_isolation1** : 'can the drainage system be isolated '

type category

explanation 'If the site drainage system is in good operational condition and is adequate for the site; the ability to isolate the system in the event of an incident such as a spill gives much greater control over what could happen to the spilt fuel. It can be contained on the site and dealt with. The site manager should be able to tell you if the drainage system can be isolated, it will be part of the procedure when a spill occurs'

options

yes - 'Yes ',

no - 'No ',

unsure - 'Not sure '.

question 'Can the site drainage system be isolated in the event of an incident at the site ? '

parameter **drainage\_test** : 'establish how often drainage system is tested '

type category

explanation 'Site drainage systems should be regularly tested for integrity. This can be done by pressure testing. '

options

more\_ten\_years - 'No evidence of testing within last ten years',

ten\_years - 'Every six to ten years ',

five\_years - 'Every two to five years ',

one\_year - 'Every two years or more often',

unsure - 'Not really sure '.

question 'How often is the site drainage system tested ? '

parameter **fill\_point** : 'What sort of fill point is used on the site for tanker deliveries '

type category

explanation 'The point of delivery of petroleum from a tanker to the site is known as the fill-point, is an area where spills etc. can occur. The area where tankers unload petroleum is usually visible from the dispensing pump area. The actual design and placing of the fill point is important, above-ground, below-ground, with or without containment. Direct fill of tanks from tanker straight to tank, is the worst case as the system can not be isolated if there is a problem. Above ground fills could be vulnerable to vehicles crashing into them and if they are not bunded any spill will reach other areas of the site but maintenance is easier. Underground fills are less vulnerable to vehicles crashing into them but if they are not properly contained, any leak or spill will be introduced directly into the ground and will by-pass any site drainage system. Site plans, the site manager and a visual inspection should be able to tell you what type of system is in use. On a modern site it is very unlikely to be direct fill'

options

- direct\_fill - 'Direct fill point '
- off\_set\_fill\_aboveground\_bund - 'Off set fill, above ground in a bunded area '
- off\_set\_fill\_aboveground - 'Off set fill, above ground no bunded area '
- off\_set\_fill\_belowground\_containment - 'Off set fill, below ground with secondary containment'
- off\_set\_fill\_belowground - 'Off set fill, below ground with no secondary containment'
- not\_sure - 'Not really sure'.

question 'What sort of fill point is used on the site for tanker deliveries ? '

picture 'fill\_point '

parameter flow\_type : 'establish type of flow '

type category

explanation 'Different types of rock strata, different ways water can pass through them. Fissure flow allows larger volume through per unit time '

options

- fissure - 'Fissure flow '
- intergranular - 'Intergranular flow '
- unsure - 'Not really sure'.

question 'What type of flow is occurring through the rock strata underlying 'site\_name' ? '

parameter gpz : 'establish which groundwater protection zone '

type category

explanation 'The Environment Agency recognises that all sources of water may be vulnerable to contamination, boreholes, springs, surface water bodies etc. For certain types of source Source Protection Zones have been defined. Those sources include:

- public supply
- private potable supply (mineral/bottled water)
- commercial food and drink production

Three zones are defined for these sources. The size and shape of these zones uses hydrogeological information such as:

- nature of underlying strata
- groundwater flow direction
- volume of water abstracted at borehole
- interference effects of other local abstractions

Zone I - called the Inner Source Protection Zone - This zone lies immediately next to the source and provides the highest level of protection. It is not defined if there is a substantial layer of low permeability strata confining the aquifer. SPZ I is defined by a 50 day travel time from any point below the water table to the source and a minimum of a 50m radius from the source. Travel time is calculated on biological contaminant decay (not petroleum decay).

Zone II - Outer Source Protection - This zone will be larger than SPZ I and is based on a 400 day travel time. This zone is not usually defined for a confined aquifer.

Zone III - Source Catchment - This zone covers the whole catchment area of the groundwater source. For boreholes this is based on the authorised abstraction rate.'

options

- I - 'Groundwater source protection zone I '
- II - 'Groundwater source protection zone II '
- III - 'Groundwater source protection zone III'
- none - 'Not in a groundwater source protection zone '

question 'Which type of groundwater protection zone is 'site\_name' located in ? '

parameter grid : ' identify site position'

type text

explanation 'An approximate grid reference is needed so the site can be identified at a later date from reports generated from this session '

question 'Please enter an approximate grid reference for 'site\_name' '

parameter interceptor : 'type of interceptor '

type category

explanation 'Interceptors or oil separators are recommended at certain types of site. These include:

- oil storage and handling areas
- industrial yard areas
- vehicle maintenance areas
- commercial vehicle parks
- large car parks
- certain lengths of motorway
- and PETROL STATIONS

Interceptors are now being made to European standards which divide them into 2 classes

Class I - with a coalescing filter when high class performance is needed

Class II - conventional gravity separators

Class I would normally be required for discharge to surface water/soakaway

The interceptor should be designed so that the maximum flow gives at least 6 minutes retention time in the interceptor. For petrol stations the minimum capacity should be greater than the maximum contents of a compartment of a road tanker likely to deliver fuel (max size usually 8,000l). The retention time can be checked by multiplying the catchment area (total area of the site) in square metres by a factor of 5, to give interceptor volume in

litres (using a standard rainfall of 50mm per hour). e.g., catchment area of 800 m<sup>2</sup>, single chamber interceptor capacity = 800 x 5 = 4000 litres. The interceptor should be a single chamber with no integral bypasses. An interceptor must have a capacity > 1 cubic metre. Any clean water from the site e.g, roof run off should not go through the interceptor. Facilities must be provided to inspect the interceptor and it must be cleaned out regularly (a routine programme of inspection should be in place).'

options

- none - 'No interceptor on site '
- interceptor\_not\_adequate - 'Interceptor present but not adequate for site '
- interceptor\_adequate - 'Interceptor present and adequate for site '
- unsure - 'Not sure if there is an interceptor or if it is adequate'.

question 'Is there an interceptor on site ?'

picture ''

parameter leak\_before : 'has the site had a leak before '

type boolean

explanation 'If there has been a previous leak or spillage at this site and the details have been recorded on the site file, this may indicate that site procedures are sub-standard and the site presents an increased risk to groundwater. This must be taken with caution as just because there is no recorded incident on file does not mean there has been no leak '

question 'Has there been a known leak or spill at the site in the past (recorded on the site file) ?'

parameter leak\_before\_vol : 'volume of previous leak from site '

type category

explanation 'The figure of 10,000 litres is approximately the size of a normal delivery tanker and as such is a "contrived" level used by groundwater specialists in assessing an incident. '

options

- ten\_thousand - 'More than 10,000 litres '
- five\_ten\_thousand - '5000 to 10,000 litres',
- less\_five\_thousand - 'Less than 5,000 litres ',
- unsure - 'Not sure '.

question 'How much product was lost during the previous incident at this site ?'

parameter leak\_detection : 'establish type of leak detection method used '

type category

explanation 'Leak detection systems are varied and one site may use more than one of those listed. The site manager should be able to tell you how he monitors his stock and be able to show you records. Leak detection systems on modern sites can be quite sophisticated. In the past they relied on tank gauging methods and wet stock records. Tank gauging using a manual dipstick is inaccurate (no account taken of temperature changes) and even done properly, an error of 0.3% will occur. There are several other options available some better than others. HARRIS wants to know the best option that is being used at 'site\_name'.

Manual tank dipping - leaks difficult to detect as method so inaccurate. Monitoring wells - not difficult to monitor but if fuel is detected it means it is already in the environment and may of already contaminated groundwater. Static leak detection - detect fall in liquid level of a tank but only during shut-down period. Continuous statistical leak detection - detects fall of liquid level in tank during quiet times when fuel is not being dispensed, good quality data obtained. Automatic wetstock reconciliation - detects a difference between fuel in tank and that dispensed - continuous system. Interstitial monitoring of pipes/lines - the space between double walled pipes can be monitored for liquid or vapour - very accurate. Interstitial monitoring of tanks - space between tank walls, filled with liquid under pressure, level of which is monitored, if it falls, there is leak - can detect leaks in both skins of the tank'

options

- manual - 'Manual tank dipping ',
- wells - 'Monitoring wells ',
- static - 'Static leak detection',
- statistical - 'Continuous statistical leak detection',
- automatic - 'Automatic wetstock reconciliation',
- interstitial\_pipe\_tank - 'Interstitial monitoring of pipes/lines and tanks',
- unsure - 'Not really sure'.

question 'What is the major method of leak detection at the site ?'

parameter leaked\_before : 'has site leaked before '

type category

explanation 'If there has been a previous leak or spillage at this site and the details have been recorded on the site file, this may indicate that site procedures are sub-standard and the site presents an increased risk to groundwater. This must be taken with caution as just because there is no recorded incident on file does not mean there has been no leak '

options

- yes - 'Yes ',
- no - 'No ',
- unsure - 'Not sure '.

question 'Has there been a known leak or spill at the site in the past (recorded on the site file) ?'

parameter o\_p\_d : 'overflow protection device '

type category

explanation 'Tanks can be fitted with a device that stops a tank being overfilled and hence cause a spill. This device or system can be designed to automatically shut off a tank (or a compartment of a tank) and prevent overfilling by

stopping fuel delivery from the tanker. Some devices work like a ball-cock in a toilet cistern, when the fuel reaches a set level, a valve automatically shuts off the delivery point and no more fuel can enter the tank. Site plans and the site manager should be able to tell you if the tanks have an overfill protection device fitted. Most modern sites do have OPD's fitted but older ones may not. '

options

yes - 'Yes ',

no - 'No ',

unsure - 'Not really sure '.

question 'Do the tanks on site have over-fill protection devices fitted ? '

picture ''

parameter permeability\_aquifer : 'establish permeability of aquifer '

type category

explanation 'Materials that allow water to flow through them are said to permeable. Permeability is a function of how porous a material is and how well those pores are connected (to allow water flow). A rock can be porous (lots of voids) but they may not be connected, so the rock would be termed impermeable. The opposite is also true, a rock may have few voids but large cracks instead, so water could pass easily and quickly through it - this type of rock would not be a good store of water. A rock that is sufficiently porous to hold water and permeable enough to allow the passage of that water is called an aquifer. Permeability can vary greatly from place to place - rocks are homogenous. This means that any designation that HARRIS uses is a gross oversimplification and is just used so that sites can be compared, it is not an absolute answer and the information can only be used in this context of carrying out a preliminary risk assessment with HARRIS.'

options

high - 'High (sands/gravels) ',

medium - 'Medium (sandstones) ',

low - 'Low (clays)',

unsure - 'Not really sure '.

question 'What is the permeability of the aquifer underlying 'site\_name' ? '

parameter petrol1 : 'establish whether petrol is stored on site '

type category

explanation 'Petroleum in the UK is sold in three different grades, leaded (red pipes), unleaded (green pipes) and super unleaded (blue pipes) which may not all be present but leaded and unleaded petrol is sold at the majority of sites. Petrol forms about 80% of retail fuel sales in the UK and is of course found at 100% of petrol stations !

Look at the dispensing pumps to check what products are being sold from the site. '

options

yes - 'Yes ',

no - 'No ',

unsure - 'Not really sure '.

question 'Does 'site\_name' store petroleum on site ? '

parameter pipe\_construction : 'evaluate type of pipe construction on site '

type category

explanation 'Although tank construction is very important when assessing risk to groundwater from a petrol station, approximately 70% of leaks can come from pipework and not the tanks themselves. Pipe construction can be similar to tank construction in that they can be made of steel, GRP etc. Most modern pipework is made of a plastic based material with built in secondary containment. As the majority of leaks occur from pipework, secondary containment is important, it usually comes in the form of a jacket for the pipe carrying the fuel and the interstitial space can be monitored for leaks. If metallic pipes are used they can be fitted with secondary containment too (double walled) and also have corrosion protection in the form of cathodic protection, both secondary containment and corrosion protection is required for metallic pipes for them to be really equivalent to plastic pipes.'

options

single - 'Steel pipes - single walled',

double - 'Steel pipes - double walled ',

non\_metallic - 'Non-metallic, no secondary containment',

*non\_metallic*\_contained - 'Non-metallic, + secondary containment ',

unsure - 'Not really sure '.

question 'How is the pipework system constructed ? '

picture 'pipework'

parameter pipe\_delivery\_system : 'type of delivery system '

type category

explanation 'There are two methods of fuel delivery through the pipework system: Suction or siphon system or Pressure system

The suction/siphon system is preferred in terms of leak prevention as once the pipe has emptied due to a leak it will not be refilled from the tank. A pressure system relies on fuel being pumped under pressure from the tank to the dispenser. If a leak develops the pump will just work harder and large leaks can develop. In the US the pressure system is used but only with line leak detection. In the UK the siphon system is more usual.'

options

suction - 'Suction/siphon system ',

pressure - 'Pressure system ',

unsure - 'Not really sure '.

question 'What kind of pipework delivery system is used to dispense fuel ?'

parameter **pipework\_age** : 'establish age of pipework'

type category

explanation 'Age of the site pipework system is also an important parameter when assessing risk to groundwater. Many leaks are often traced back to pipework systems not tanks. In a survey of London petrol station leaks, up to 70% of leaks were traced to pipes (Thompson, 1992)'

options

more\_than\_thirty - 'Over 30 years old',

twenty\_to\_thirty - '20 - 30 years old',

less\_than\_twenty - 'Less than 20 years old',

unsure - 'Not really sure'.

question 'How old is the oldest pipework system on site ?'

parameter **pipework\_age1** : 'establish age of pipework'

type category

explanation 'Age of the site pipework system is also an important parameter when assessing risk to groundwater. Many leaks are often traced back to pipework systems not tanks. In a survey of London petrol station leaks, up to 70% of leaks were traced to pipes (Thompson, 1992). Pipes may suffer from increased stress during installation that creates weak spots e.g. bending a metal pipe. They may not be replaced when an associated tank is replaced.'

options

yes - 'Yes',

no - 'No',

unsure - 'Not really sure'.

question 'Do you know roughly how old the oldest pipework system is (to within 10 years) ?'

parameter **pollutant\_type1** : 'evaluating what has been spilled before'

type category

explanation 'If there has been a previous incident at 'site\_name' there may be (should be!) a record of what was spilled or leaked, even if it only says petrol or diesel'

options

petrol - 'petroleum',

diesel - 'diesel or DERV',

other - 'something else'

unsure - 'Not really sure'.

question 'What was leaked or spilled in the previous incident recorded on file ?'

parameter **pollutant\_type\_specific** : 'what type of pollutant is being investigated'

type category

explanation 'Choose a type of pollutant that best describes the type of substance that has leaked from the site or been spilt at the site. If it is a tank or pipework leak the site manager should be able to tell you what has been leaked. If it is a spill on delivery the tanker driver will know what sort of product he was delivering and again the site manager will also know. A spill on dispensing from pump to vehicle will usually be visible near the dispensing pump. If it is a multiple pump (more than one product dispensed) the site manager may be able to help.'

options

petrol - 'leaded petrol',

petrol\_unlead - 'unleaded petrol',

super\_unlead - 'super unleaded petrol',

diesel - 'diesel or DERV',

mineral\_oil - 'mineral oil'

fuel\_oil - 'fuel oil'.

question 'Which pollutant are you investigating ?'

parameter **pump** : 'what sort of dispensing pumps'

type category

explanation 'The type of pump used at the site can vary. Modern pumps should conform to a British Standard BS 7117, which among other things means that a check valve is fitted at the dispenser base and not at the tank top (check valves ensure that fuel flows from the tank to the dispenser). The standard of the pump will be on a plate attached to the pump.'

options

pump\_no\_standard - 'Electric pump with no standard',

pump\_3002 - 'Pumps to SFA 3002 Standard',

pump\_7117 - 'Pumps to BS7117',

not\_sure - 'Not really sure'.

question 'What standard of pumps are used on the site for dispensing fuel to the customer ?'

picture 'plate'

parameter **pump\_island\_seal** : 'finding out if pump islands are sealed'

type category

explanation 'Where the pump island joins the forecourt could provide an escape for any spills to by-pass the drainage system. So these joints must be sealed and the seal intact.'

options

yes - 'Yes',

no - 'No',



unsure - 'Not sure '

question 'Are the pump islands sealed at the forecourt/island junction and in good condition ?'

parameter **pump\_type\_est** : 'estimating pump type '

type category

explanation 'Pump types can vary depending on age. Most modern pumps should be designed to BS7117. A small plate on the side of each pump states to what standard the pump has been designed to '

options

plate\_BS7117 - 'Plate on pumps - BS7117 ',

plate\_not\_BS7117 - 'Plate on pumps - SFA3002 ',

no\_plate - 'No plate on pumps ',

modern\_site - 'Site is of a modern appearance and seems to of been refurbished since 1988 ',

old\_site - 'Site looks old and has probably not been refurbished since 1988' .

question 'Choose one of the following options '

parameter **risknumber** : 'risknumber is an aggregate of all scores '

type number

parameter **severity1** : 'calculation of site risk number '

type text

explanation ''

/\* rules field \*/

rules

'high' if risknumber >= 296,

'medium-high' if risknumber <=295.9 and risknumber >= 251,

'medium' if risknumber <= 250.9 and risknumber >= 207,

'medium-low' if risknumber <= 206.9 and risknumber >= 162,

'low' if risknumber <=161.9.

parameter **site\_name** : 'site name and location'

type text

explanation 'The name and location of the site must be recorded in order to provide a "paper-trail" of the decisions made with regard to this site. Just type a short name and location such as Shell petrol station, Solihull Road. You do not have to type in the full address of the site.'

question 'What is the name and location of the site you are investigating ?'

parameter **site\_type** : 'site type or activity for assessment '

type category

explanation 'Please choose one sort of site or type of activity for this session. At the moment HARRIS focuses on retail petroleum sites only but in reality petroleum hydrocarbons can be found at a variety of sites such as oil storage depots etc. HARRIS has been designed with these other sorts of sites in mind. '

options

petrol\_filling\_station - 'Petrol filling station ',

fuel\_depot - 'Fuel distribution depot ',

oil\_storage\_operation - 'Oil storage operation',

solvent\_storage - 'Solvent storage operation',

solvent\_recovery\_operation - 'Solvent recovery operation',

transport\_hydrocarbons - 'Hydrocarbon transport'.

question ' 'site\_name', is what type of site ?'

picture ''

parameter **strata\_type** : 'establish type of strata '

type category

explanation 'Strata type is a function of groundwater vulnerability and will affect how much impact a leak from 'site\_name' may have. '

options

clay - 'Mainly clay type ',

sandstone - 'Mainly sandstone type ',

limestone - 'Mainly limestone type ',

unsure - 'Not really sure'.

question 'What type of strata is found underlying 'site\_name' ?'

parameter **tank\_age** : 'establish age of tanks '

type category

explanation 'Age of tanks is an important parameter to evaluate when assessing risk to groundwater. Tanks over 30 years old are significantly more likely to leak than younger tanks as they are more likely to be made of steel. The national tank population still contains many older tanks (Thomson, 1992). GRP tanks are more modern and are more likely to fail very early in their operational life due to incorrect installation. Steel tanks are still the most popular variety in the UK'

options

more\_than\_thirty - 'Over 30 years old ',

twenty\_to\_thirty - '20 - 30 years old ',

less\_than\_twenty - 'Less than 20 years old',

unsure - 'Not really sure '

question 'How old are the oldest tanks on site ?'

**parameter tank\_age1 : 'establish tank age '**

**type category**

**explanation** 'Age of tanks is an important parameter to evaluate when assessing risk to groundwater. Tanks over 30 years old are significantly more likely to leak than younger tanks as they are more likely to be made of steel. The national tank population still contains many older tanks (Thomson, 1992). GRP tanks are more modern and are more likely to fail very early in their operational life due to incorrect installation. Steel tanks are still the most popular variety in the UK '

**options**

yes - 'Yes ',

no - 'No ',

unsure - 'Not really sure '.

**question** 'Do you know roughly how old the oldest tanks are (to within 10 years) ? '

**parameter tank\_construction : 'evaluate type of tank construction on site '**

**type category**

**explanation** 'Tank construction can vary enormously between sites (and on the same site) Site plans, the site manager and the licensing officer should be able to supply some of the details necessary to complete these questions. Otherwise age of the site will be used and a worst case scenario of single skin steel tanks will be used. The oldest tanks are made of single skin steel (and are the most likely to suffer from corrosion damage etc.). More modern tanks include:

Single skin Glass Reinforced Plastic (GRP)

Double skinned steel tanks

Double skinned GRP tanks

Steel tank with a polyurethane jacket (supertank)

Double skinned tanks have two walls with a space in between called the interstitial space (this can be used for monitoring tank integrity i.e., to see if the tank has leaked). Tanks can also be relined, this will create an interstitial space. Single skinned tanks are the cheapest but if there is a failure in one wall a leak will definitely occur and no interstitial monitoring can take place. The Agency or the Institute of Petroleum does not recommend that single skin tanks be used on any new sites or sites being re-developed'

**options**

single\_steel - 'Single skin steel tanks ',

double\_steel - 'Double skin steel tanks ',

grp - 'Glass Re-inforced Plastic tanks ',

steel\_grp - 'Steel tanks with a polyurethane jacket ',

unsure - 'Not sure'.

**question** 'How are the tanks at 'site\_name' constructed ? '

**parameter tank\_test : 'how often are tank/pipework systems tested '**

**type category**

**explanation** 'Even if a site has a tank/pipework system which complies with all recommended standards, the system can still deteriorate with time. By integrity testing the system regularly, any leaks can be detected early. The site manager may be able to show you records of system testing for the site.'

**options**

more\_than\_ten - 'No evidence of testing in previous ten years ',

ten\_years - 'Every ten years ',

five\_years - 'Every five years',

one\_year - 'Annually',

unsure - 'Not really sure '.

**question** 'How often is the tank/pipework system tested for integrity ? '

**parameter tank\_vol : 'operational tank volume '**

**type category**

**explanation** 'When assessing a site as a whole, total operational tank volume is an important factor. Tank sizes vary but the risk posed to groundwater must be based on a total volume not just individual tank size. If you are not sure what volume the tanks are, answer not really sure and HARRIS will estimate based on another question. '

**options**

hundred\_thousand - 'More than 100,000 litres',

fifty\_hundred\_thousand - '50,000 to 100,000 litres ',

less\_fifty - 'Less than 50,000 litres',

unsure - 'Not really sure'.

**question** 'What is the total operational tank volume at 'site\_name' ? '

**parameter tank\_vol\_est : 'estimating tank vol based on site type '**

**type category**

**explanation** 'A crude method of estimating tank volume can be based on the type of site under investigation. A motorway service station that is open 24 hours a day will have a far larger operational tank volume than a rural out of town filling station on a minor road with a greater site throughput '

**options**

motorway - 'On a motorway or other major route ',

town - 'Within a built-up area or a supermarket ',

rural - 'Out of town on a more minor road '.

**question** 'Where is 'site\_name' ? '

**parameter target\_affected : 'an identified target has been affected '**

**type category**

**explanation** 'Targets or receptors of pollution are not uniform in nature. For this assessment they may include:

- drinking water abstractions (public/private)
- agricultural abstractions - for irrigation, watering livestock
- industrial abstractions - for cooling waters etc.
- SSSI"s or nature reserves etc.
- surface water bodies such as rivers/streams (not ditches)
- groundwater as a resource in its own right

Of course the ultimate target most often considered by risk assessment methodologies is man himself. This assessment treat the groundwater as the target but if that becomes polluted then other targets may be affected such as man via drinking water or flora and fauna via surface water for example. A further category of target could be added here - that of residential buildings, with or without cellars.'

**options**

- yes - 'Yes',
- no - 'No',
- unsure - 'Not really sure'.

**question** 'Do you definitely know that a target has been affected by previous polluting incidents from 'site\_name' ? '

**parameter target\_location : 'find out how far from the site any target is '**

**type number**

**explanation** 'The distance from the site to any potential target is very important in terms of risk to the target. Groundwater itself can be a target. Distances here are in metres and the greatest distance considered is 10,000m or 10km. '

**range** 0 10000

**question** 'How far away from 'site\_name' is the closest potential target in metres ? '

**parameter target\_type : 'the type of target that may be affected '**

**type category**

**explanation** 'HARRIS is asking you to identify targets that are near, so what is near. Distance to a target is a function of what that target is. So for example a drinking water abstraction 1km away from 'site\_name' will be under greater potential risk from 'site\_name' than say a surface water body at the same distance. Distances of up to 10km are considered by HARRIS.

**Targets or receptors of pollution are not uniform in nature. For this assessment they may include:**

- drinking water abstractions (public/private) including food/drink uses
- agricultural abstractions
- industrial abstractions
- SSSI"s or nature reserves etc.
- surface water bodies such as rivers/streams (not just a ditch)
- groundwater as a resource, a target in its own right

Of course the ultimate target most often considered by risk assessment methodologies is man himself. This assessment treat the groundwater as the target but if that becomes polluted then other targets may be affected such as man via drinking water or flora and fauna via surface water for example. A further category of target could be added here - that of residential buildings, with or without cellars.'

**options**

- drinking\_abs - 'Drinking water abstraction ',
- agi\_abs - 'Abstraction for agricultural use ',
- ind\_abs - 'Abstraction for industrial use',
- nature - 'SSSI, nature reserve etc. '
- water - 'Surface water bodies'
- gw - 'Groundwater as the target',
- unsure - 'Not sure what is nearby'.

**question** 'Can you identify any of these potential targets near 'site\_name' now ? '

**parameter target\_type\_affected : 'type of target affected in previous incident '**

**type category**

**explanation** 'Targets or receptors of pollution are not uniform in nature. For this assessment they may include:

- drinking water abstractions (public/private)
- agricultural abstractions - irrigation, watering livestock
- industrial abstractions - cooling waters
- SSSI"s or nature reserves etc.
- surface water bodies such as rivers/streams (not ditches)
- groundwater as a resource, a target in its own right

When carrying out a risk assessment the ultimate target is often man himself. For this assessment with HARRIS, groundwater itself is considered the target or the risk of concern. Groundwater is considered a target as if it does become polluted then man may be affected via drinking water for example and the environment may also be affected e.g. pollutants entering surface water from groundwater. These systems do not operate in isolation, groundwater is part of the water cycle. '

**options**

- drinking\_abs - 'Drinking water abstraction ',
- agi\_abs - 'Abstraction for agricultural use ',

ind\_abs - 'Abstraction for industrial use',

nature - 'SSSI, nature reserve etc. '

water - 'Surface water bodies',

gw - 'Groundwater as a resource',

unsure - 'Not really sure'.

question 'What type of target was affected by this previous incident at 'site\_name' ? '

parameter type\_others : 'type of product on site not petrol/diesel '

type category

explanation 'The majority of retail petrol-filling stations in the UK sell petroleum and diesel fuels. Some do provide other products such as:

mineral oil

fuel oil

paraffin '

options

mineral\_oil - 'Mineral oil',

fuel\_oil - 'Fuel oil ',

paraffin - 'Paraffin ',

none - 'None of these',

unsure - 'Not really sure'.

question 'Are any of these other products stored in tanks at 'site\_name' ? '

## APPENDIX D

### PEOPLE WHO PARTICIPATED IN THIS RESEARCH AS POTENTIAL SYSTEM USERS, ADVISORS OR SOURCES OF EXPERTISE

#### D.1 Potential System Users

Ian Barker - Environment Agency, Southern Region  
Alan Cansdale - Environment Agency, Southern Region  
Rosemary Cansdale - Environment Agency, Southern Region  
Richard Dean - Environment Agency, Southern Region  
Jackie Harrison - Environment Agency, North West Region  
Phil Heath - Environment Agency, North West Region  
David Holden - Environment Agency, North West Region  
John Ingram - Environment Agency, North West Region  
Robin Lancefield - Sir William Halcrow and Partners  
Miranda Luckwell - Environment Agency, Southern Region  
Francis Lowe - Environment Agency - North East Region  
Lesley Moore - RPI Ltd  
Liz O'Neill - Environment Agency, North West Region  
Anthony Parsons - Environment Agency, North West Region  
Martin Rattigan - London Borough of Enfield  
Katie Smith - Environment Agency, North West Region  
Miranda Stewart - London Borough of Enfield  
Jonathan Taylor - Environment Agency, Southern Region  
Mark Thewsey - Environment Agency, North West Region  
Andrew Turk - Conoco Ltd  
Rachel Turner - Luton Borough Council  
Nick Wharton - South Lakeland District Council  
Ian Withers - Environment Agency, Southern Region

#### D.2 Advisors and Sources of Expertise

Allan Crowe - National Water Research Institute, Canada  
Alan D'Arcy - Environment Agency, North West Region  
Ian Foster - Environment Agency, North East Region  
Bob Harris - National Groundwater and Contaminated Land Centre, Environment Agency  
Ian Hill - Environment Agency, Anglian Region  
David Lerner - University of Bradford (now at Sheffield)  
Steve McNeeley - Office of Underground Storage Tanks, United States Environmental Protection Agency, USA  
Tony Peacock - Environment Agency, North West Region  
Peter Phelan - University of Lancaster  
Heather Sheeley - CAMR  
Jonathan Smith - Environment Agency, Thames Region  
Steve Stanbra - Environment Agency, North East Region  
Trevor Stapleton - BP Oil Ltd  
Bogden Wasikowski - Lubrizol Ltd  
Hal White - Office of Underground Storage Tanks, United States Environmental Protection Agency, USA