

Development of a catchment risk assessment procedure
for the protection of potable water supply intakes

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Abstract

Water supply companies operating within the European Union (EU) have a statutory duty to provide water that is wholesome to drink. To ensure continued compliance with EU water quality regulations together with reductions in operating costs it is necessary to optimise the use of raw water supplies. In order to do this successfully, a knowledge of the potential risks to water quality within a supply catchment is required. This thesis describes the development of a novel methodology to assess pollution risks in public water supply catchments. The Risk Assessment of Supply Catchments And Land (RASCAL) methodology consists of four interrelated stages to identify, estimate, evaluate and manage risks to water quality. The methodology is generic in nature thus allowing the transfer of the approaches developed to other catchment areas.

The potential of geographical information systems (GIS) as a tool assessing pollution risks in supply catchments is identified from an extensive review of water quality hazards and the use of GIS in the UK water industry. This potential is explored further through the example application of the RASCAL methodology to the Upper Wharfe catchment area.

The thesis describes an important development in assessing catchment risks, the construction of catchment-scale hazard maps using logical structures (Source Trees) and GIS data models. In this way, the probable extent of point and diffuse sources of pollution are identified for the entire catchment area of a surface water intake. The use of generically available digital data allows the production of hazard maps for ten water quality issues potentially affecting the Upper Wharfe source. These digital hazard maps are also used in the development of a raw water sampling programme. The results from this programme confirm the ability of the digital maps to identify the source of water quality hazards using generic data.

Quantitative approaches relying on the acquisition of large amounts of historical or background data are found to be inherently inappropriate for a generic methodology. The availability of water quality data is identified as a fundamental barrier to the successful preparation of such quantitative frequency estimates. This research combines quantitative and qualitative approaches to provide a valid methodology of risk assessment for generic application.

A fundamental characteristic of the methodology developed is this mixture of quantitative, semi-quantitative and qualitative techniques encompassed within it. This represents a significant contrast to the traditional hard-engineering approaches to risk assessment applied in past studies where the emphasis has been on the quantitative estimation of risk. The use of digital data and GIS allow the most suitable technique to be identified and displayed.

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Chapter 1

Introduction and thesis aims

1.1 Public water supply intakes and catchment water quality

Clean, safe water is fundamental to human life as it is vital for drinking, cooking, cleaning, sanitation and a host of other activities in modern society. The estimated per capita consumption rate for the UK is 140 litres per day, around three percent of which is used for drinking and food preparation. The remaining 130+ litres are used primarily for toilet flushing, bathing and cleaning (Gray, 1994).

In England and Wales, the Water Supply Companies (WSCs) have a statutory duty under the 1989 Water Act to supply water for human consumption that is “wholesome”. Wholesome water is defined by reference to more than fifty chemical, microbiological and aesthetic parameters in the drinking water quality legislation. The quality of water intended for human consumption in the UK is subject to two main regulatory controls. Firstly, the raw water abstracted from surface waters must comply with the criteria specified in the Surface Waters (Classification) Regulations (HMSO, 1989b), the values specified for individual parameters are dependant on the nature of the treatment works in place. Secondly, after treatment the quality of the water must meet the standards specified in the Water Supply (Water Quality) Regulations (HMSO, 1989a). Both these pieces of legislation originate from earlier European Community Directives (75/440/EEC and 80/778/EEC respectively). The legislative requirement to comply with these regulations, therefore minimising the risk to the health of consumers, is the primary regulatory driving force behind water supply companies treatment and distribution activities.

Over half of Britain’s drinking water is obtained from surface water abstractions. Many of these abstraction points are situated in upland areas where historically, the quality of raw water is less exposed to pollution. However, the physical nature of upland supply catchments and the activities operating in them may result in a number of water quality problems and it is therefore important to assess the possible risks of pollution upstream of the point of abstraction. Major pollution incidents affecting intakes on the River Dee in 1984 and the River Severn at Worcester in 1995 have highlighted the need for abstractors to be aware of the activities taking place upstream of an intake site. Costs associated with the 1995 Worcester incident were in excess of one million pounds.

There exists therefore an immediate need for supply companies to assess the risk of contamination to their surface water intake sites. This research therefore aims to identify a generic methodology for this assessment of risk, suitable for application to upland catchments such as those found in Yorkshire. The optimal management of a surface water intake relies on a thorough understanding of the risks to water quality present in a catchment. In order to assess these risks in a suitable, generic manner a methodology must be developed with a sound theoretical background and rigorous framework. Example application to a major surface water intake is used to facilitate and enhance this development.

The river catchment has long been considered a suitable spatial scale for the research of water quality issues. Smith (1976) in his seminal text *Water in Britain* drew attention to the catchment unit as the fundamental scale for research into hydrology and water quality. Chorley's (1969) book *Water, Earth and Man* is also a benchmark text in catchment scales studies. Considerable catchment scale research has been carried out since then (see McDonald & Kay, 1988; Kay & McDonald, 1992 and Newson, 1992; for reviews of such work).

The catchment area of a river provides an appropriate spatial unit of study for the investigation of pollution risks as not only do they contain land managed on a (notional) catchment basis, but these are (largely) hydrologically distinct areas. The transfer of pollutants between catchments will usually only result from human interference in the hydrological system (e.g. diversions, catchwaters and pipeline transfers), or through groundwater percolation. Newson (1992) also highlights the importance of an understanding between land management and water resources and quality in the wider scope of the sustainable management of catchment areas.

The reorganisation of the UK water industry into Regional Water Authorities based broadly on hydrological catchment areas has also stimulated planners to approach the optimisation of water quantity and quality on a catchment basis due to the jurisdictional and managerial boundaries imposed by the 1973 Water Act. This also provided new opportunities for the planning and management of the water environment on a catchment scale (Woolhouse, 1994). Catchment scale studies have been further encouraged by the creation of Agenda 21, the United Nations programme of action for sustainable development, in which Section 18.9 states that integrated water resources management, including land and water related aspects, should be carried out at the catchment basin or sub-catchment level (UN, 1992).

Increasing commercialisation of the UK water industry following the 1989 privatisation has led to the need for companies to justify expenditure and reduce costs in all areas of the business. Increasing demand has led to the need to optimise the use of water resources. It is therefore fundamentally important for companies to be aware of the security of their supplies and how the nature of their supply catchments can influence water quality. The optimal use of resources and therefore protection from contamination will also be important when companies are aiming to increase their customer base in the face of increasing competition in the water industry.

A coherent methodology for identifying risks to water quality in existing catchments and to facilitate the exploitation of new resources will therefore be a fundamental tool for water supply companies in the future.

1.2 Risk assessment as a tool for intake protection

The water industry in general is aware that no catchment can be considered as entirely free from pollution and the industry's own Association identifies the need to "*maintain procedures for the inspection of catchment areas*" (Water Authorities Association, 1988, p.9). However, supply companies are often unaware of the risks in their catchment areas, particularly in upland catchment areas that are traditionally considered "safe" in terms of water quality. An assessment of the activities in these areas will therefore provide operational managers and strategic planners with valuable information for use in resource optimisation and waste minimisation. As such, the environmental benefit of such an approach will be realised by more efficient use of our most fundamental of natural resources.

When surface water intakes were originally set up, some assessment of the pollution risk was carried out. This is evident in the location of the intakes in the Yorkshire region, predominantly situated on upland rivers with limited development in the catchment areas. However, this assessment probably only involved speculation based on the local knowledge and experience of the operational staff and decision-makers, rather than a formal structured assessment process that could be applied consistently to all proposed sites.

Lamb & Keller (1987) and Cole *et al.* (1988) produced the first formal approaches to assessing risks to surface water intakes a decade ago. These were in response to the River Dee incident in 1984 during which over 700 litres of pure phenol were released into the river upstream from several potable supply intakes. Since then, research efforts in this discipline have concentrated on groundwater contamination (Morrey *et al.*, 1995) or like Lamb & Keller (1987) and Cole *et al.* (1988) have addressed the problems arising from large industrial premises in river catchments (Keller & Wilson, 1992; Fryer & Davis, 1995). Improvements in treatment technology together with this apparent lack of interest in non-industrialised catchments has led to a relative dearth of research into the assessment of pollution risks to drinking waters abstracted from upland river catchments. As will be discussed in Chapter 2, these catchments play a vital role in the security of supplies to the Yorkshire region.

Risk assessments are becoming involved in all aspects of operational water management. Lumbers & Cook (1993) identified the need to incorporate risk assessment methods in capital planning, operational activities and especially the optimisation of water supplies. The potential for application of risk assessment concepts in an industry as complex as the supply of water are therefore numerous.

An indication of the growing application of risk assessment techniques are the recent establishment of centres of "risk excellence" by two of the world's most influential environmental bodies. Both the US Department of Agriculture and the UK Environment Agency are investing heavily in risk assessment-based approaches to environmental management.

Senior figures in the UK water industry have also embraced the potential of risk assessment. Banyard (1995) identifies the potential of probabilistic risk assessments combined with local / expert knowledge as a necessary replacement for the current approach of managing by people's perceptions of good practice.

Risk assessment therefore represents a framework within which current and developing scientific knowledge can be harnessed to provide an improved understanding of water quality issues and processes. As such it is ideally placed to assist in activities to safeguard the quality of raw water supplies.

1.3 GIS and risk assessment – the untapped potential

Geographical information systems (GIS) are computer-based software programmes designed specifically for the storage, analysis and display of spatially referenced data. The process of pollution risk assessment requires the assimilation of data that are spatially variable in nature, making geographical information systems (GIS) an ideal tool for such assessments.

Wadge *et al.* (1993a) found GIS to be appropriate tools for the analysis of hazards and assessment of risks as they have the ability to analyse spatial patterns, manage inductive and deductive modelling routines and calculate statistical probabilities. Hewitt (1993) offered a fundamental link between risk assessment and GIS with the following:

“One necessary component of risk assessment is the coupling of models with information systems, like GIS, in order to mimic the risk mapping that occurs in our minds”

(Hewitt, 1993, p.316).

The potential to formalise the process of risk assessment, formally the domain of the risk assessors' "expert knowledge", therefore exists with GIS. Rejeski (1993) also identifies the potential of GIS to assist in the development of more generic, transferable approaches to risk assessment:

“[there exists] the possibility of using the GIS... to 'regionalise' the risk analysis process -- moving it from its traditional focus on site-specific problems to a true macro-scale planning and policy tool”

(Rejeski, 1993, p.11).

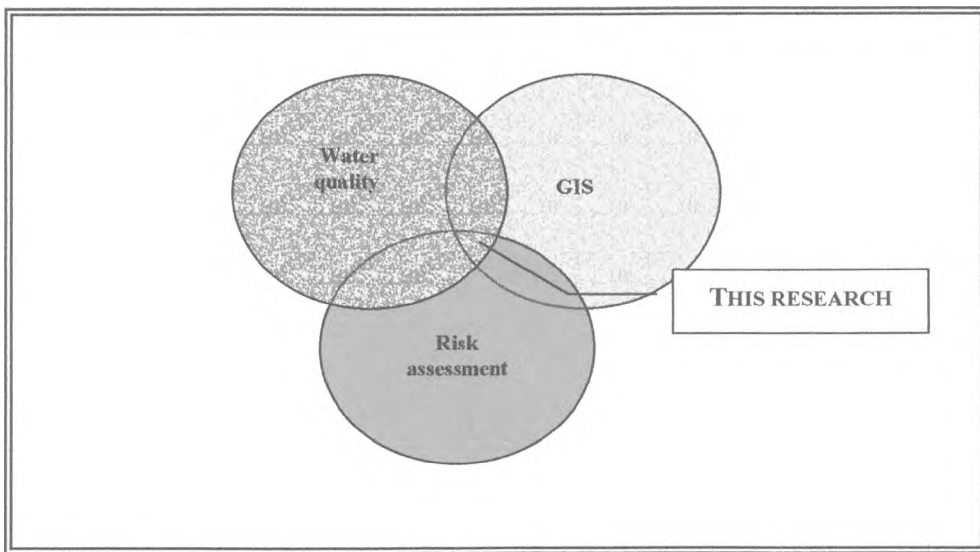
The application of GIS-based risk assessment to surface water intake catchments has not previously been explored and this approach therefore provides immense potential for the development and application of a novel methodology. There is little evidence of GIS-based water quality hazard mapping of this variety evident in the literature (see only Breach *et al.*, 1994, Smith *et al.*, 1996, Foster *et al.*, 1997 and Foster & McDonald, 1998).

Currently, organisations across the water industry are beginning to appreciate and develop the potential of GIS technology, coupled with moves towards pro-active management of resources through the prediction of risks and problems. The formulation of a methodology to assess pollution risks in a water supply catchment which utilises the power of GIS to handle large, spatially referenced datasets is therefore particularly timely.

1.4 Research aims

To summarise the above discussion, drinking water quality, environmental risk assessment and geographical information systems are three fields of environmental research that are rapidly developing and all may impact on the activities of water supply companies. However, to date their development has been very much confined to individual disciplines with limited interaction at either the research or applied level. This research therefore aims to investigate the area of overlap identified between these disciplines, as illustrated in Figure 1.1 below.

Figure 1.1 Theoretical context of the research



By combining contributions from these three research areas it is envisaged that an enhanced, generic methodology for assessing pollution risk in supply catchments can be developed.

The primary aim of this research is to develop a methodology using GIS technology to assess pollution risks to potable water supply intakes such as those in the Yorkshire region. The methodology will be based on the use of commercially accessible GIS software and data, secondary data archives (such as national statistical records) and field studies. This will allow the methodology to be applied on other catchment areas in the future, creating a generic, consistent approach to the assessment of pollution risks.

The development of a new methodology also aims to avoid many of the potential pitfalls associated with traditional risk assessment techniques by integrating the appropriate use of qualitative, semi-quantitative and quantitative assessments. This is in contrast to recent multi-stage methodologies such as those of Fryer & Davies (1992) and Pollard *et al.* (1995) where qualitative, semi-quantitative and quantitative assessments are distinguished and carried out separately.

In order to assess the potential of the methodology developed here, example scenarios will be tested on the Lobwood intake in the Upper Wharfe catchment area. The Lobwood intake is of major strategic importance to the supplies of the Yorkshire region. As a major river intake in what it is considered to be a “safe” catchment, the site is especially suitable for use in this research. With no plans for capital investment at this site, an assessment of the risks in the catchment is especially important for ensuring the future security of the resource.

In achieving the primary aim of the development of a new methodology the research also aims to:

- Identify the optimum theoretical framework for the assessment of risk to water quality from catchment activities
- Develop and test a number of methods of identifying hazards to water quality
- Investigate the potential of GIS-based techniques for risk assessment activities, especially through the creation of catchment hazard maps.
- Identify hazards to water quality using GIS-based modelling and hazard mapping by example application to a test catchment area (the Upper Wharfe).
- Investigate potential methods for estimating hazard frequency and identifying and communicating the potential consequences of a risk event suitable for generic applications.

It is not intended that an all-encompassing methodology for assessing and managing risks will be created for use by intake managers. Moreover, the intention is to investigate the potential for using digital spatial data, geographical information systems, current knowledge of catchment processes and simple modelling to identify potential hazards, estimate their rates of occurrence, evaluate their consequences and suggest possible management options. The research aims to contribute to the small base of knowledge on GIS-based risk assessments through a novel application to surface water intake protection and to improve the management of such intakes.

1.5 Thesis structure

Chapter 2 introduces contemporary issues in drinking water quality, placing them within the current legal framework and assessing recent trends in water quality compliance. The history of the legislative control over water supply and quality is described and the current status and possible future format of this legal framework discussed. In the investigation of recent compliance with the water quality legislation, particular attention is paid to the performance of Yorkshire Water Services Ltd., within whose operational area this research is conducted. The quality of drinking water supplied throughout the region from 1990 to 1996 is reviewed, as is the incidence of pollution events in the source waters of these supplies. The final section discusses the protection of water gathering grounds (such as intake catchments) as a proactive philosophy for water quality control.

Geographical information systems (GIS) have been identified above as a potential tool for conducting risk assessments. Chapter 3 describes the characteristics of a GIS and reviews their use in the water industry of England and Wales. The past use of GIS in operational management, hydrological modelling and environmental risk assessment is discussed in order to identify the potential of recent developments in GIS and computing technology for the assessment of risks to surface waters.

Chapter 4 introduces some of the fundamental concepts of risk and risk assessments and places drinking water risks in the wider social science context of the risk assessment field. Examples of environmental risk assessment approaches are used to identify the fundamental framework of a successful risk assessment methodology. Chapter 5 then develops this review to identify and appraise the limiting factors in previous assessments of water quality risk assessments, from which the methodological framework of a new risk assessment process is developed. Subsequent chapters develop this theoretical framework by application to the Lobwood intake catchment.

Chapters 6 and 7 describe the development of GIS-based techniques for hazard identification. This work represents the bulk of the evolution of the methodology. Particular emphasis is placed on the development of novel techniques for identifying water quality hazards. Central to this is the exploitation of GIS technology to map potential hazard source areas.

Chapter 8 describes the development of a raw water sampling programme designed using the GIS techniques and hazard maps developed in the previous chapters. The results from this are then used to investigate the relationships between the hazard maps and observed water quality in the catchment. Sample results are also used to suggest areas where water quality processes are poorly understood and provide examples of development opportunities. Chapter 9 applies and “field tests” the concepts identified in earlier chapters to estimate the frequency of hazard occurrence and identify risk consequences. Chapter 10 concludes the study by outlining the methodology developed and assessing the success of the approaches employed in the various stages of the risk assessment process. Potential areas for the exploitation of the novel concepts developed here are discussed and recommendations for future research proposed.

Chapter 2

Drinking water quality

2.1 Introduction

This chapter discusses several major themes central to the derivation of a generic methodology for assessing risks to the quality of drinking water supplies. Firstly (Section 2.2), the quality of drinking water is considered, including the history of water supply and drinking water quality regulations. An understanding of this information is fundamental to establishing the required quality of modern drinking water, what problems are commonly experienced and why risk assessments are required to reduce the occurrence and impact of poor quality drinking water. Compliance rates of drinking water within the UK as a whole and Yorkshire in particular are then discussed (Section 2.3) together with a summary of recent trends in surface water pollution incidents (Section 2.4). Changes in approaches to the protection of water resources are highlighted, including catchment-based water quality research and catchment management initiatives (Section 2.5). The chapter concludes by highlighting the potential to improve drinking water quality through the control of catchment areas. In order to carry out such control in an effective manner, actions have to be prioritised, therefore necessitating the need to identify and assess pollution sources in water supply catchments

2.2 Drinking water legislation

The quality of water supplied to homes and industry as potable water (water intended for human consumption) will be influenced by the quality of the original resource, the treatment processes undertaken and the nature of the distribution system. Legislative standards are stipulated for raw waters abstracted for treatment, and treated water intended for supply as potable water. These quote allowable concentrations and values for a number of physical, chemical and microbiological parameters. Levels of the parameters mentioned in these regulations beyond the maximum admissible levels, can therefore be considered to be a potential pollution incident as far as drinking water abstractors are concerned.

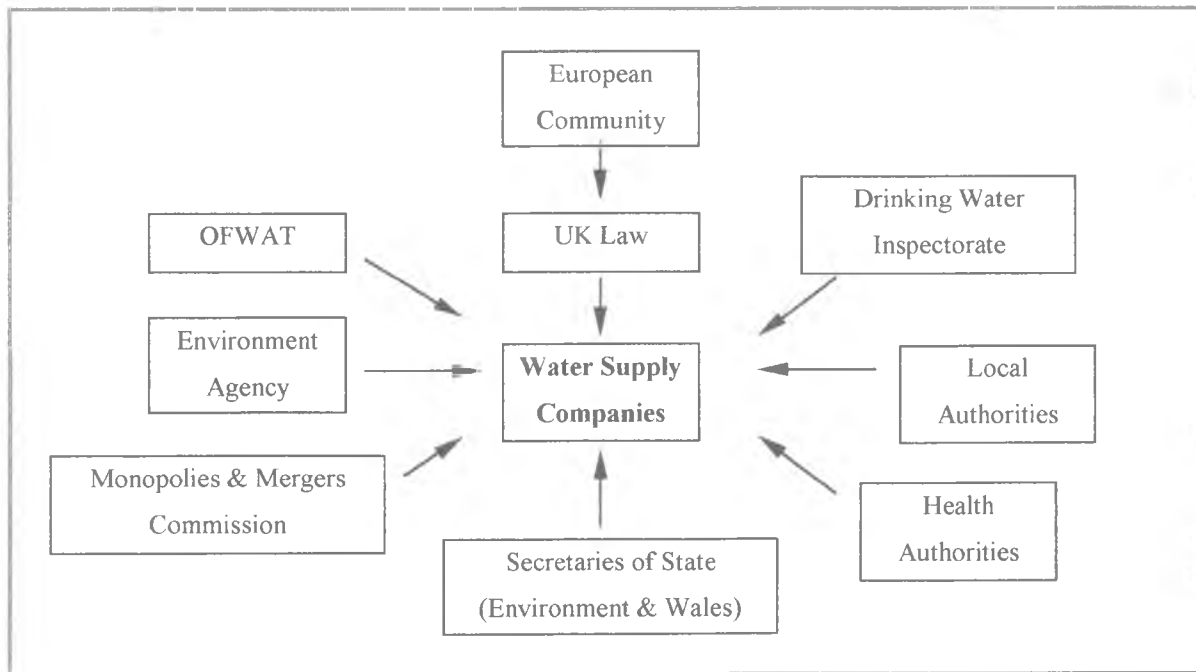
The development of water quality legislation in England and Wales is inextricably linked to the development of the present water industry structure. In England and Wales water planning began in effect with the 1848 Public Health Act, although water bailiffs, and controls on activities in river catchments existed from the sixteenth century. This act charged local authorities with the responsibility for providing members of the public with clean and wholesome water for consumption. In the early twentieth century there were 2,160 water undertakings, including 786 local authorities (OFWAT, 1993). The 1945 Water Act and the 1948 River Board Act reorganised the management of water resources of England and Wales into 32 'River Boards' based on large catchment areas.

This was the first occasion that water resource planning had been considered on a catchment basis. During the 1960s it was recognised that it was no longer possible to meet the water demands of many areas on a catchment basis. Furthermore, with the quantities of water used in inter-catchment transfers and grid supply systems increasing, the River Authorities were reorganised by the 1973 Water Act to established 10 multi-purpose water authorities (OFWAT, 1993). These authorities were responsible for water supply, wastewater treatment, effluent disposal, pollution control and ecological monitoring (i.e. they were responsible for both pollution disposal and the protection of the aquatic environment). Following recognition that the organisations responsible for the protection of the aquatic environment should be independent of those responsible for waste water effluent disposal, the 1989 Water Act was enacted to separate the 'poachers' from the 'gamekeepers'. This act also resulted in the privatisation of the water companies.

At present in England and Wales, the responsibility for water supply lies with the water supply companies (WSCs). The 1989 Water Act resulted in the formation of ten privatised water service companies that are responsible for both water supply and the handling of wastewater. The area covered by each water service company is approximately based on the former boundaries of the regional water authorities established under the 1973 Water Act. Each region has a single water service company to handle wastewater, but may have several water supply companies. For example in the Yorkshire region, sewage and wastewater is handled solely by Yorkshire Water Services Ltd, but both Yorkshire Water Services Ltd and York Waterworks plc supply potable water.

There are two forms of regulatory control on the water undertakers, economic regulation and environmental regulation. For England and Wales, the 1989 Water Act is the most influential piece of recent legislation as this also restructured the regulation and enforcement activities. The 1989 Water Act made the Secretary of State, the Director General of Water Services and the National Rivers Authority (NRA) the principal regulators. The responsibilities of the NRA have subsequently been transferred to the Environment Agency following the 1995 Environment Act. A summary of the organisations that collectively regulate the industry in England and Wales is shown in Figure 2.1.

Figure 2.1 Regulation of the water supply and service companies in England & Wales



(after Gray, 1994)

A brief description of the role of each of the organisations is given below.

European Community:- The EC regulates the activities of the water industries throughout Europe, principally by the introduction of EC Directives on environmental and water quality. These are enacted in the UK through the implementation of *UK Law*.

OFWAT:- OFWAT (the Office of Water Services) is responsible for ensuring the water and sewerage companies in England and Wales provide consumers with a good quality, efficient service at a fair price. OFWAT is a government department led by The Director General of Water Services (the Director). The Director is the economic regulator of the water industry, with responsibilities for setting price limits, protecting the standards of service, promoting economy and efficiency and ensuring that competition can develop. The Director also reports annually on the performance of different companies.

Environment Agency:- The Environment Agency is a non-departmental public body established by the 1995 Environment Act. It is sponsored by the Department of the Environment with policy links to the Welsh Office and the Ministry of Agriculture, Fisheries and Food. The Environment Agency has taken over the functions of its predecessors, the NRA, Her Majesty's Inspectorate of Pollution, Waste Regulatory Authorities and some parts of the Department of the Environment. The regulatory functions of the Agency that impact on the WSCs include flood defence, water resources, pollution control, fisheries, navigation, recreation and conservation.

DWI:- The Drinking Water Inspectorate is the primary organisation involved in the regulation of the quality of drinking water supplies. The Inspectorate acts as a technical assessor on behalf of the Secretaries of State, and provides advice on all aspects of the water industry, to both consumers and the industry itself.

Monopolies & Mergers Commission:- Regulates the economic and business activities of the water service companies.

Secretaries of State (Environment & Wales):- have the power to appoint technical assessors to ensure that water companies are conforming to their legal obligations.

Local Authorities & Health Authorities:- have responsibilities for monitoring the 'wholesomeness' of the water in terms of public health issues.

Many of the regulatory controls on environmental and drinking water quality in the UK originate from EC legislation. The 1987 Single European Act states that environmental considerations should be incorporated in all other legislation i.e. considerations of the effect on the environment become an intrinsic part of all legal documents. There are three types of European Law; Regulations, Directives and Decisions. Regulations are directly applicable law in any Member State. They are immediate and valid in all of the Community Member States. Directives are where the Community stipulates certain objectives to be achieved. Member States are given a time frame in which to implement legislation in their own legal system in order to achieve these objectives. Decisions are legally binding but only apply to the party to which they are directed. This party may be a Member State, an industrial sector, or an individual company.

The majority of environmental legislation in force in the UK is a result of EC Directives. The initial piece of European legislation affecting English law concerning surface abstractions for drinking water quality was the 1975 European Council Directive concerning the quality required of surface water intended for the abstraction of drinking water in Member States (75/440/EEC). Standards are set for 46 physical, chemical and microbiological parameters. In this Directive, surface waters are divided into three categories A1, A2 and A3 depending on the nature of the treatment that the water will receive. The types of treatment in each category are shown in Table 2.1 below. Surface waters that have characteristics failing the A3 standards must not be used as a source of drinking water.

Table 2.1 Standard methods of treatment for transforming surface water categories A1, A2 and A3 into drinking water (EC Directive 75/440/EEC)

Category	Treatment Types
A1	Simple physical treatment and disinfection, e.g. rapid filtration and disinfection.
A2	Normal physical treatment, chemical treatment and disinfection, e.g. pre-chlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorination).
A3	Intensive physical and chemical treatment, extended treatment and disinfection, e.g. chlorination to break-point, coagulation, flocculation, decantation, filtration, adsorption (activated carbon), disinfection (ozone, final chlorination).

Physical, chemical and microbiological parameters are stipulated at two levels. Mandatory (*I*) values must be adhered to in the resultant national legislation. Where no *I* value is stipulated, Member States must endeavour to respect the guide (*G*) values. Member States may set more rigorous standards but are under no obligation to stipulate standards where no value is set (EC, 1975). Strict levels are set determining the proportion of samples that may fail to reach the required standard prior to the water body being deemed to fail. Exceptions to the Directive are allowed, subject to approval by the Commission,

but must not disregard public health. Directives 75/440/EEC and 79/869/EEC (stipulating the sampling and analysis standards for the 1975 Directive) were adopted in the UK with the enactment of The Surface Waters (Classification) Regulations 1989 (HMSO, 1989b).

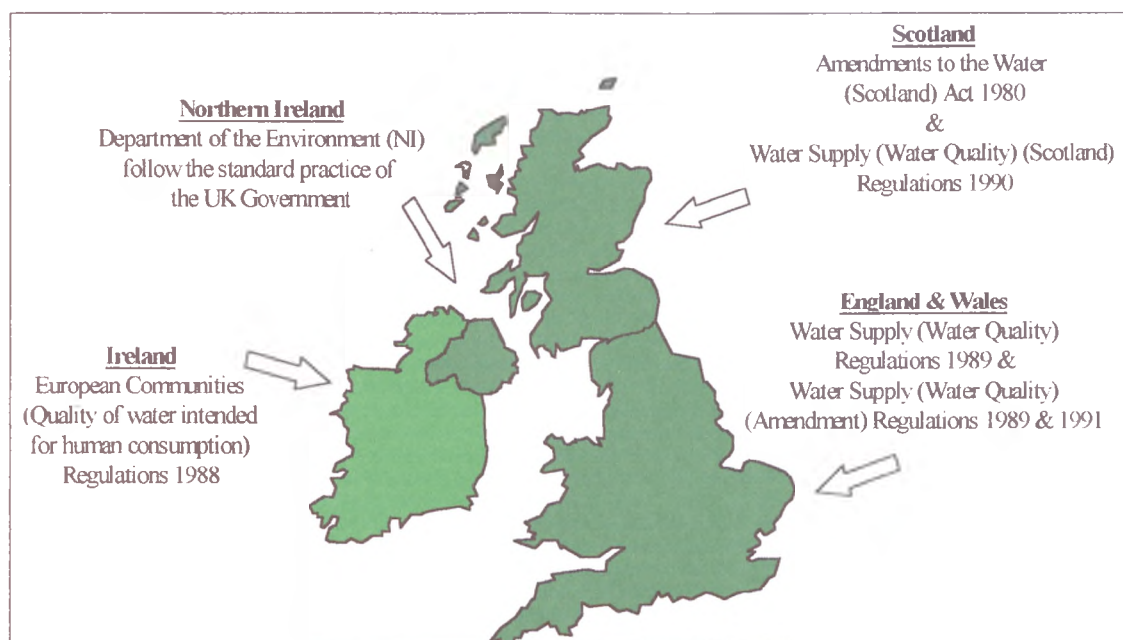
The primary piece of legislation that governs the quality of treated drinking water within the European Community is the Council Directive 80/778/EEC relating to the quality of water intended for human consumption (EC, 1980), commonly referred to as the Drinking Water Directive (DWD). This Directive relates not only to all water supplied as drinking water, but also to that used in the production of food or in the processing or manufacture of products intended for human consumption. It does not cover the quality of natural mineral waters, which are controlled through a separate Directive.

Sixty-six drinking water parameters are stipulated in the Drinking Water Directive, which are categorised into six groups. Two maximum admissible concentrations (MACs) may be stipulated. As with the earlier Directive on surface waters (75/440/EEC) the mandatory (*I*) values should be adhered to in Member States, whilst the guide (*G*) values are a long term aim to work towards. No time scales are set in either Directive for the achievement of the guide values. Both *G* and *I* are not stipulated for all parameters, resulting in large variations in the standards actually adopted within Member States. The Drinking Water Directive also stipulates the method of analysis for each parameter, the minimum acceptable compliance rates and the required sampling frequency.

The 1980 EC Drinking Water Directive was enacted throughout the British Isles between 1980 and 1991. The regulations were brought into Scottish and Irish Law through amendments to existing legislation in 1980 and the introduction of the further Regulation in 1988 and 1990. The Directive was enacted in England, Wales and Northern Ireland by the introduction of the 1989 Water Supply (Water Quality) Regulations and subsequent amendments in 1989 and 1991. A summary of the adoption of Directive 80/778/EEC is shown in Figure 2.2 below.

The Water Act 1989 places a duty on water companies to supply only water that is wholesome at the time of supply (DWI, 1994). Wholesomeness is defined in the Water Supply (Water Quality) Regulations by reference to 55 water quality parameter standards. Also stipulated are rules governing the determination of sampling locations, sampling frequency, provisions for sampling at treatment works, service reservoirs and new resources, water treatment methods (including the prevention of contamination during distribution) and record maintenance and publication.

Figure 2.2 Enactment of the EC Drinking Water Directive (80/778/EEC) in the British Isles



The Regulations in England and Wales incorporate all of the mandatory standards set out in the Drinking Water Directive, including national standards for eleven parameters. However, the UK regulations only specify the mandatory values laid out in the Directive and take little account of the guide values towards which member states are supposed to be working. For many parameters the lower guide value is the only one specified in the Directive, and these are subsequently omitted from the regulations.

Just three parameters within the regulations are set to more stringent levels than the EC Directive requires. The Prescribed Concentration Values (PCVs) for Copper and Zinc are based on the EC guide value (although no MAC is set out in the Directive). The PCV for phosphorus is set lower than the MAC value, but higher than the suggested guide value (EC MAC = $5000\mu\text{g l}^{-1}$; EC guide = $400\mu\text{g l}^{-1}$; PCV = $2200\mu\text{g l}^{-1}$). For the eleven parameters quoted in the EC DWD but omitted from the UK Regulations, neither mandatory or guide values are set out in the DWD. The stipulation of standards for these is therefore optional for Member States. Several standards in the Directive are dependant upon external factors such as temperature but no account is taken for this in the UK Regulations (e.g. Fluoride).

The 1989 Water Supply (Water Quality) Regulations can therefore be seen as adopting little more than the bare minimum standard of the original Directive. This could be indicative of the UK water industry's lack of confidence in the Directive. The regulations do however contain a 'catch-all' clause in that drinking water must not contain any substance that is detrimental to public health (HMSO, 1989a). Failure of this clause can result in legal action against the WSCs and therefore represents a major benchmark for assessing drinking water quality in England and Wales.

In developing the Drinking Water Directive, the EC was criticised for failing to consult with water industry experts in the member states, basing their findings purely on the work of their own scientists. Some national standards are based on the findings of the World Health Organisation (WHO). The potential loss of this expert knowledge base should be avoided with the revised Directive as the EC has sought extensive input from the water industries of all member states (Breach, 1995).

2.2.1 The future of drinking water legislation in England & Wales

In 1995 a fundamental review of water policy was called for by the European Council and the Environment Committee of the European Parliament. In 1996 the European Community published its proposals for the revision of water policy in member states (EC, 1996). The resultant Water Resources Framework Directive, is intended to amalgamate water-related policy in the European Union, to co-ordinate the implementation of existing Directives and identify gaps in the current legislation. All of this is to be carried out at the river basin (i.e. catchment) scale (Campbell, 1996). As Breach (1995) noted, the Commission has consulted the water industries of member states in the preparation of the new Directive. The Framework Directive will also consider the improved scientific and technical knowledge gained since the original Directive was prepared in 1975 (EC, 1996; Breach, 1995).

The establishment of the Framework Directive will result in the repeal and replacement of the 1975 Surface Water Directive (and the related Directive on sampling and analysis, 79/869/EEC) together with a number of other Directives on fish and groundwater.

As yet no new parameters or values have been established for the quality of drinking water (or water abstracted for drinking) to replace those specified in these earlier Directives. The Water Resource Framework Directive is not scheduled for implementation until at least the year 2005 (Campbell, 1996) but any assessment of pollution risk based on regulatory standards must take into consideration these impending changes to the regulatory controls on water supply quality. Transparency to regulatory change is therefore an important factor of any risk assessment methodology, in order to allow flexibility and constant revision in the future.

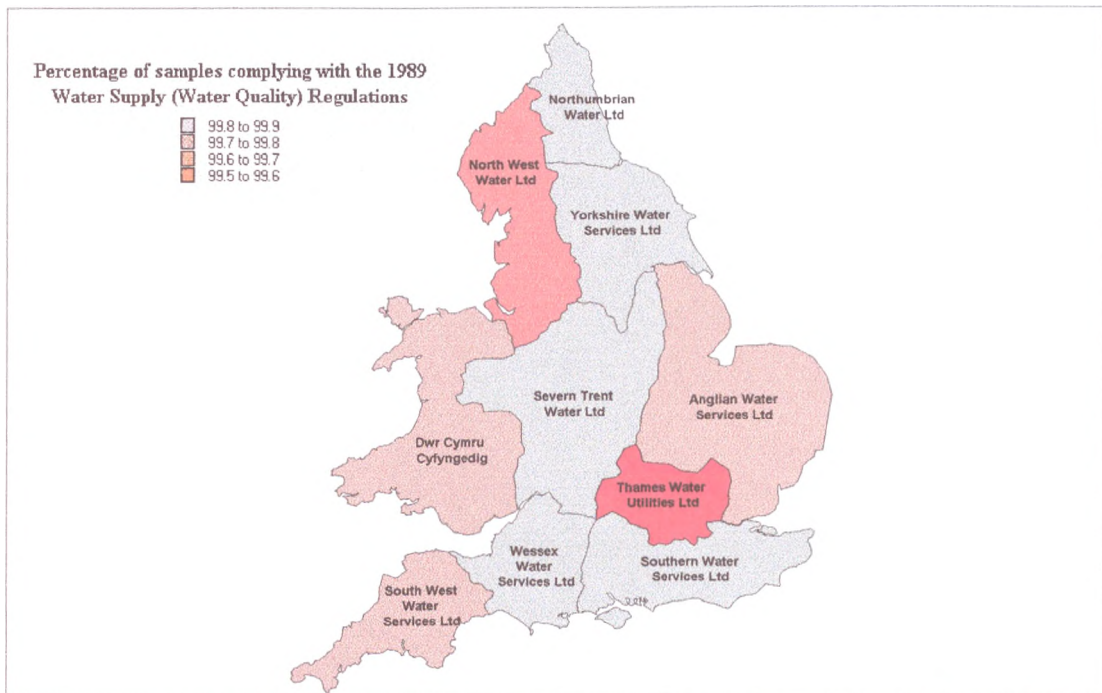
2.3 Drinking water quality in England & Wales (1990 - 1996)

Meaningful comparisons of the drinking water quality of EC Member States is difficult due to differences in sampling, analysis and result interpretation between the different states (DWI, 1997). Fawell & Miller (1994) investigated reports of quality infringements in published papers, highlighting problems involving pesticides, nitrate, lead, coliforms and iron. The authors concluded that, in general, the quality of UK supplies compare favourably with those of other Member States. Recent initiatives resulting from the EC Standardised Reporting Directive and the establishment of the new Framework Directive should allow more informed comparisons in future years (DWI, 1997).

Water undertakers in England & Wales have a statutory obligation to report on the quality of their drinking water. Since 1990 companies have submitted annual returns to the Drinking Water Inspectorate (DWI), summarising their compliance with the 1989 Water Supply (Water Quality) Regulations. The Regulations stipulate 100% compliance as the legal requirement for the water suppliers. Study of compliance rates can provide an important source of initial information for risk assessors looking at pollution risks to potable supplies.

The overall compliance rates in 1996 of the ten major water service companies are illustrated in Figure 2.3. The figure shows the percentage of all samples taken during 1996 that comply with the relevant standards in the 1989 Water Supply (Water Quality) Regulations. It is important to note that these values only indicate the percentage compliance rates with the water quality standards and will be influenced by the source of the water supplies, the treatment processes in use and the frequency of sampling. Care must therefore be exercised when drawing comparisons between the companies' performance using these data. In order to reduce the impact of different sampling intensities, only percentage overall compliance is considered.

Figure 2.3 Drinking water quality in the 10 water service companies (1996)
(Percentage of samples complying with the 1989 Water Supply (Water Quality) Regulations)

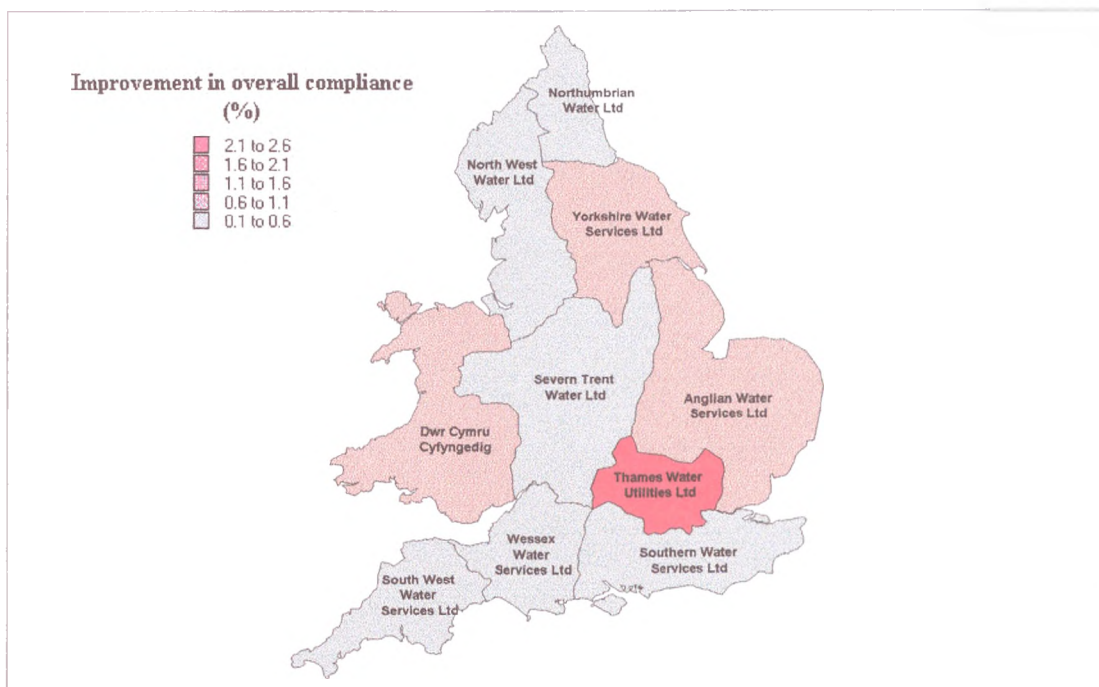


(Source – DWI, 1997)

Thames Water Utilities Ltd. and North West Water Ltd. had the worst compliance rates in 1996 (99.5% and 99.6% respectively). Slightly better were Anglian Water Services Ltd., South West Water Services Ltd. and Dwr Cymru Cyfyngedig (99.7% compliance). The remaining five large water service companies achieved 99.8% compliance in 1996.

The poorer performance of Thames Water Utilities Ltd. is attributed to the high proportion of drinking water in the Thames region that is obtained from surface abstractions from polluted lowland rivers (75%). Of the 0.5% of tests that failed the standards, the most significant were for Nitrite and Isoproturon (a chemical herbicide). There were also some failures to meet the standards for coliform bacteria, iron, nitrate and some pesticides (DWI, 1997). The results were however an improvement on compliance rates in 1995 where the majority of failures were the result of high levels of pesticides and were in supply zones where improvement programmes were being undertaken. Many such 'undertakings' were finished in December 1995. The improved results of Thames Water Utilities in 1996 illustrate the impact of improvement programmes on general compliance rates. Figure 2.4 shows how the overall compliance of each company has changed since the implementation of the 1989 Regulations (compiled from the annual DWI reports: DWI, 1991 to 1997).

Figure 2.4 Overall improvement in drinking water quality compliance in the 10 water service companies between 1990 and 1996
(percentage of samples complying with the 1989 Water Supply (Water Quality) Regulations)



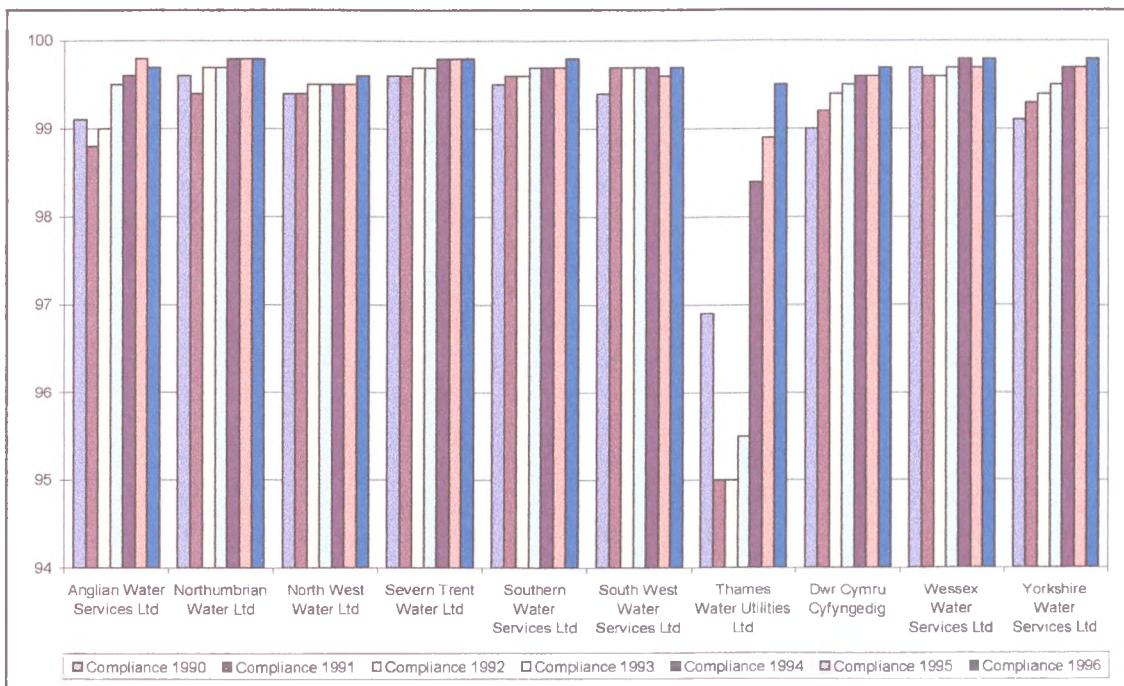
(Sources – DWI 1991, 1992, 1993, 1994, 1995, 1996 & 1997)

All the companies have improved their levels of compliance between 1990 and 1996. The greatest improvements have taken place in the Thames region (dark red shading), although this region has had the poorest compliance rate each year. The areas showing the smallest improvement are those with higher initial compliance rates, e.g. Severn Trent Water Ltd. and Wessex Water Services Ltd., where the rate of compliance has consistently been 99.6% or above. In addition to water quality failures, several companies did not comply with the required sampling frequencies specified in the regulations. This was mainly during 1990, the first reporting period following the enactment of the regulations. Abnormally

high levels of compliance in the first year (1990) for several companies are believed to be the result of such failures to follow the correct sampling requirements, hence giving anomalous compliance rates.

The annual changes in compliance for individual companies are shown in Figure 2.5. The general trend is one of increasing compliance, with 1996 representing the best compliance rates. One exception is Anglian Water Services Ltd., whose compliance rate fell between 1995 and 1996 by 0.1% (following continuous improvement since 1991). This fall in performance was attributed to an increase in compliance failures for Potassium, although only five of the 809 Potassium tests were below the PCV standard (DWI, 1997).

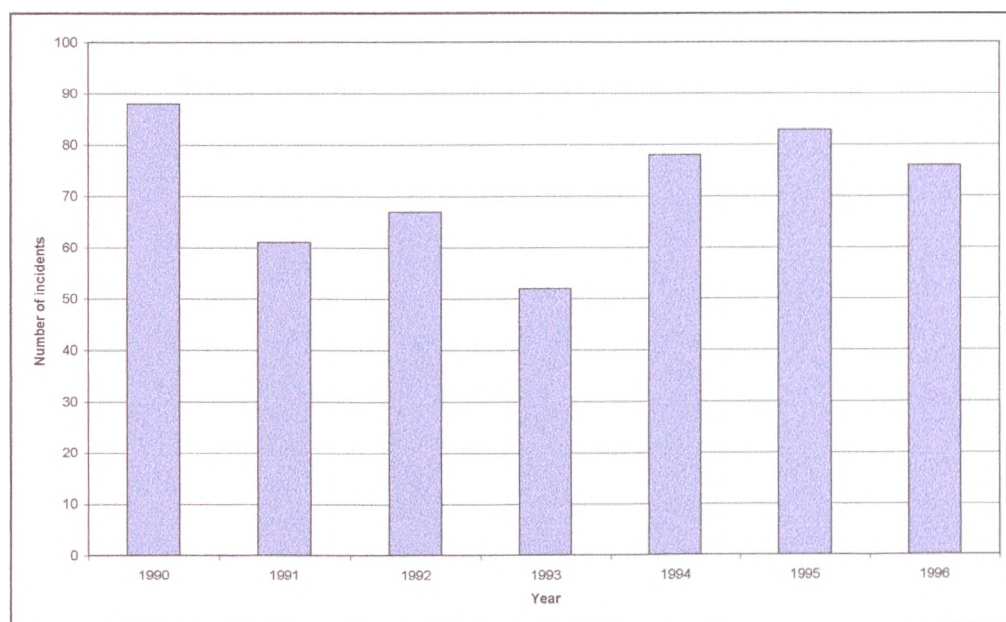
Figure 2.5 Annual changes in drinking water quality compliance in the 10 water service companies (1990 – 1996)
(percentage of samples complying with the 1989 Water Supply (Water Quality) Regulations)



(Sources – DWI 1991, 1992, 1993, 1994, 1995, 1996 & 1997)

The improvements seen since 1990 are mainly due to legally binding commitments to improve treatment practices and upgrade treatment works, such as those carried out by Thames Water Utilities Ltd. In some cases, improvements have also been made as a direct result of combining improved treatment with catchment control initiatives (see for example, Breach & Porter, 1995; Court *et al.*, 1995) illustrating the potential of catchment management to have a positive impact on the performance of water companies.

WSCs are also required to inform the Secretary of State of incidents likely to affect public health, attract publicity, cause concern to customers or that are potentially of national significance (DWI, 1997). The occurrence of such incidents since the formation of the DWI in 1990 is summarised in Figure 2.6. From 1992 the sources of some incidents were classified depending on their cause, as shown in Table 2.2.

Figure 2.6 Number of potable supply quality incidents reported to the DWI (1990 – 1996)

(Sources – DWI 1991, 1992, 1993, 1994, 1995, 1996 & 1997)

Investigation of the frequency and sources of potable water quality incidents notified to the DWI indicates the major supply quality problems facing the industry, and is therefore of particular use to risk assessors as this information can be used to inform assessors of the likely contamination scenarios that may be encountered. As can be seen from Figure 2.6 and Table 2.2, the number of reported incidents varied between 50 and 90 incidents each year, with disinfection failures and the contamination of water following bursts being the most common sources of water quality problems.

Table 2.2 Causes of potable supply quality incidents reported to the Drinking Water Inspectorate (1992 – 1996)

Cause	1992	1993	1994	1995	1996
Disinfection failures	10	9	23	12	12
Microbiological contamination of water discovered on, or traced to, service reservoirs	8	7	5	8	8
Microbiological contamination of water in distribution systems, probably not implicating service reservoirs	7	10	7	13	7
Contamination occurring after mains bursts or during repairs or other associated work on mains including rezoning	9	15	16	21	32
Detection of <i>Cryptosporidium</i> or <i>Giardia</i> in water supplies	9	2	-	3	6
Backflow into water mains	5	4	6	3	3
Advisory concentration for pesticides exceeded	2	1	1	2	-
Chemical contamination associated with treatment works	-	-	11	11	7
Chemical contamination associated with water sources	-	-	-	4	1
Other	6	4	9	6	-

(Data collated from DWI, 1993; 1994; 1995; 1996; 1997)

The contamination of drinking water following incidents affecting the water source has been reported separately since 1995 (Table 2.2). This, in part, illustrates the increasing importance associated with the pollution of the source waters and the desire to control pollution in the catchment source areas (thus transferring the cost of remedial action). Following the report of four incidents in 1995, only one was identified in 1996.

Of the four incidents associated with contaminated source water reported in 1995, one was reported by Anglian Water Services Ltd., involving an abnormally high, naturally occurring taste and odour in raw water. The substance is not identified by the Drinking Water Inspectorate report (DWI, 1996). North East Water Plc reported the bacterial contamination of a rural spring supply and two occurrences of pesticide pollution were reported. Severn Trent Water Ltd., reported a contamination of supply abstracted from the River Avon by MCPA and Northumbrian Water Ltd., and the occurrence of DDT in two spring sources (DWI, 1996). The incident reported during 1996 involved the contamination of source water treated by North West Water's Wayoh treatment works. Contamination by Geosim resulted in complaints of unusual tastes and odours by customers. The source of this chemical is believed to be the presence of Actinomycete organisms in the raw water entering the works (DWI, 1997).

Whilst some information of previous events can be gleaned from formal reports of incidents, a risk assessment of water source areas has the potential to identify other types and sources of potential incidents. This will enable customers and the supply companies to identify and prioritise the need for remedial actions to reduce the impact of pollution incident scenarios. Consideration of regional datasets and pollution incident data can assist in this and is discussed below.

2.3.1 The quality of potable supplies in the Yorkshire Water region

As reported in the previous section, more than 99% of all drinking water samples taken annually in the Yorkshire Water region between 1990 and 1996 complied with the 1989 Water Supply (Water Quality) Regulations. The overall rates of compliance can be seen in Figure 2.6. A summary of the failure of PCVs for individual parameters (over the period 1990 to 1996) is shown in Table 2.3 below.

Table 2.3 shows that major problems were experienced with alkalinity and hardness failures during the period 1990 to 1992. These were the result of poor treatment efficiency at water treatment works and were addressed by a number of undertakings by the supply company. No compliance failures were experienced between 1993 and 1996 for either alkalinity or hardness, illustrating the success of the improvement schemes at the works involved. Improvements during 1996 of the high failure rates for trihalomethanes (down to one third of the 1995 levels) is also attributed to the commissioning of major new treatment plants in Leeds and Sheffield (Yorkshire Water Services Ltd., 1997).

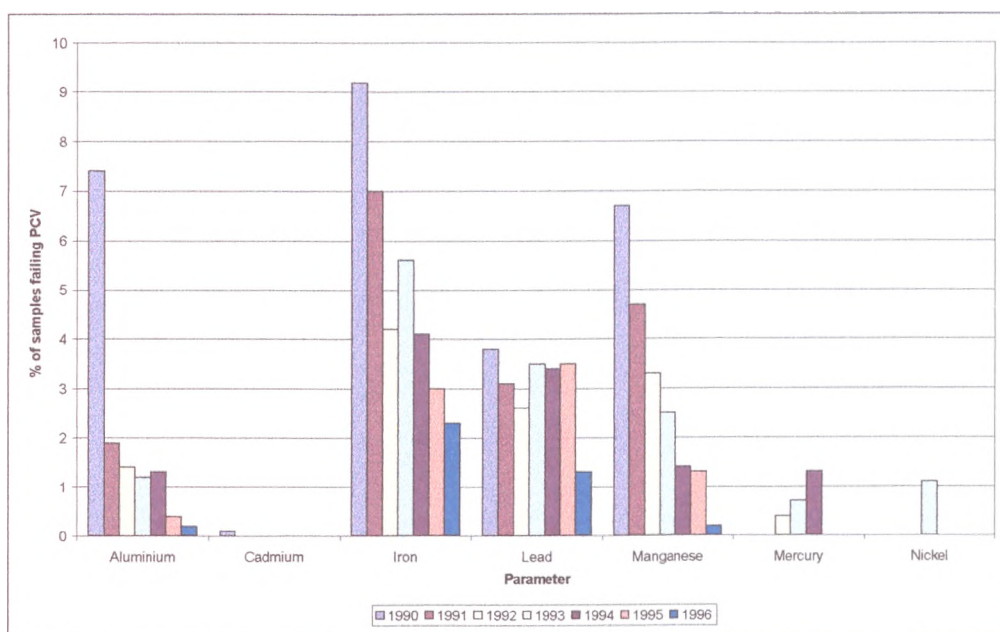
Table 2.3 Samples failing the PCV (Prescribed Concentration Value) in the Yorkshire Water region – as percentage of those taken (1990 – 1996)

Parameter	1990	1991	1992	1993	1994	1995	1996
2,4 - D				0.1	0.6		0.1
Alkalinity	23.5	15.0	48.9				
Aluminium	7.4	1.9	1.4	1.2	1.3	0.4	0.2
Atrazine	1.2	1.2					
Benzo 3,4 pyrene	0.4	0.1	0.4	0.3	0.2	0.3	0.2
Cadmium	0.1						
Chlorotoluron	0.8				0.7		
Coliforms Total	1.9	1.6	1.2	1.0	0.7	0.7	
Colour - filtered	0.9	0.7	0.3	1.3	1.0		
Diazinun		0.4					
Diuron				0.3	0.6		
Faecal coliforms	0.6	0.3	0.2	0.2			
Fenitrothion		0.5					
Fluroxypyr				0.6			
Hardness	17.6	12.6	23.9				
Heptachlor							0.1
Imazapyr					0.1		
Iron	9.2	7.0	4.2	5.6	4.1	3.0	2.3
Isoproturon	1.9	1.1	0.6	2.6	3.4	5.2	1.0
Lead	3.8	3.1	2.6	3.5	3.4	3.5	1.3
Linuron							0.1
Manganese	6.7	4.7	3.3	2.5	1.4	1.3	0.2
MCPA		0.4	1.8	2.3	1.7	0.1	
MCPP			3.5	7.9	4.2	1.4	0.7
Mercury			0.4	0.7	1.3		
Nickel				1.1			
Nitrate	0.2		0.3	0.3	0.1	0.6	0.7
Nitrite	0.9	0.7	0.4	0.4	0.1	0.2	
PAH	1.2	1.7	1.4	1.9	1.8	3.0	3.86
Permanganate index	0.4	2.5	0.3		3.1	0.8	
Pesticides (Total)			1.2	1.6	2.3	0.0	0.1
pH	0.8	0.4	0.5	0.3	0.3	0.1	0.2
Phosphorus							0.3
Propyzamide			0.2				
Simazine	2.1		0.6	0.2			
Taste		0.1	0.1	0.1			
Temperature	0.1						
Total Ammonium				3.0			
Trichloroethylene	0.1						
Trihalomethanes	12.9	7.2	10.4	11.9	7.2	3.0	0.9
Turbidity	0.4	0.4	0.4	0.3	0.4	0.3	0.4

Source: Yorkshire Water Services Ltd. (1997)

High failure rates for metal parameters have been experienced throughout the reporting period as illustrated in Figure 2.7 below. Failures of the PCV for lead, resulting from contamination by pipes have been significantly decreased in 1996 as a result of the installation of phosphate dosing at many treatment works (Yorkshire Water Services Ltd., 1997). Dosing treated waters with phosphate reduces its plumbosolvency, thus reducing the contamination of water by lead pipework. Initial findings show that the compliance rate of samples with the EC's proposed new limit of $10\mu\text{g}\text{l}^{-1}$ for lead was improved by 10% as a result of phosphate dosing.

**Figure 2.7 Percentage of samples failing the PCV in the YWS region
Metals - (1990 to 1996)**

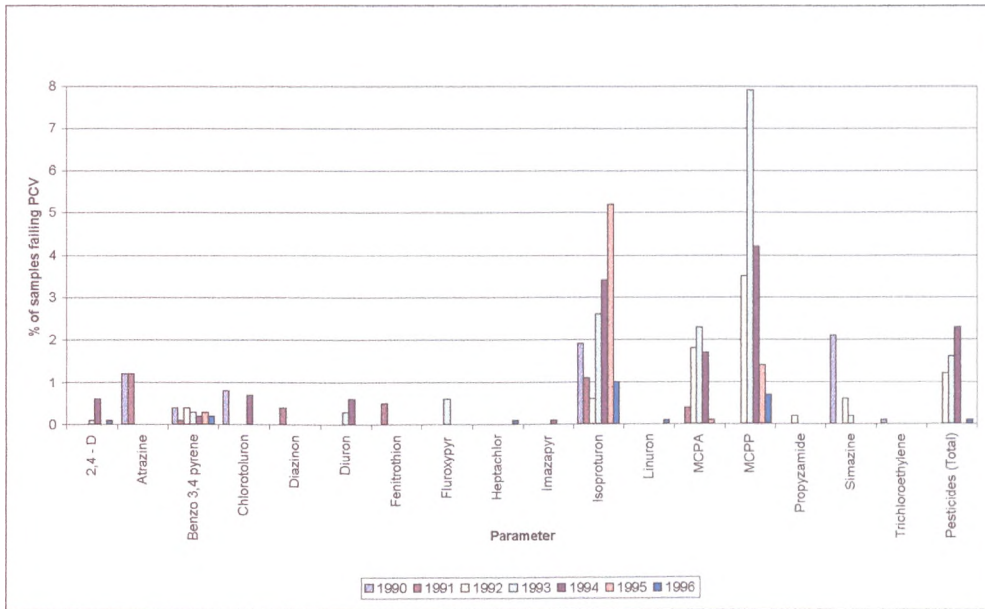


Source: Yorkshire Water Services Ltd. (1997)

PCV failures of aluminium, iron and manganese have all declined since 1990, primarily due to the completion of a major programme of improvements in treatment efficiency. Failures of mercury, cadmium and nickel have not been experienced since 1994, 1990 and 1993 respectively.

The microbiological quality of drinking water in the YWS supply area has also improved since 1990 (see Table 2.3). Again this is attributed to improvements in treatment efficiencies. An increase in the failure of PAH (Polycyclic Aromatic Hydrocarbons) compared to previous years is thought to be a combination of the change from relaxed values during 1990 to 1995, and the increased deterioration of coal-tar pipe linings. Failure of the PCVs for total and individual pesticides shows little discernible trend during the reporting period 1990 to 1996 (see Table 2.3 and Figure 2.8 below), although Isoproturon and MCPP are the most common causes of PCV failures amongst the pesticides monitored. Diffuse agricultural sources in supply catchment areas may be the primary source of these failures.

**Figure 2.8 Percentage of samples failing the PCV in the YWS region
Pesticides - (1990 to 1996)**



Source: Yorkshire Water Services Ltd. (1997)

The quality of drinking water in the YWS region is seen to be high, and in general has improved since the first DWI reporting period (1990). Particular improvements are evident during 1996 as a direct result of the improvement programmes completed by the end of 1995. However, the contamination of source waters by pesticides is a problem and during 1996 YWS reported a number of pollution incidents that potentially affected the quality of potable supplies.

Of the 16 incidents reported to the DWI during 1996, several were the result of the contamination of raw water supplies. A diesel spillage in a river intake catchment in January coincided with a period of high demand. This demand meant that the intake works could not be closed and detectable odour remained in some treated water. Cryptosporidium were detected in treated waters on several occasions, with contaminated raw water supplies representing the most likely sources.

The summary of drinking water quality over the last 6 years in the YWS operating region is, like the national data summarised before it, an important indicator of the problems that need to be addressed in any pollution risk assessment. This regional scale data, widely available through public register access, can also highlight local contamination problems not evident from national summaries (e.g. particular problems with Isoproturon and MCPP).

2.4 Water pollution incidents in England & Wales

The importance of river abstractions to the supply of potable water in Yorkshire was outlined in Chapter 1. An investigation of surface water pollution incidents can be used to inform risk assessors of the potential types of pollution hazard experienced within a catchment area, the return period of occurrence and the potential sources of contamination of the water body.

The comparison of water pollution incidents over time is problematic as the reporting organisation boundaries and the methods of reporting have changed. The standard pollution incident classification system was last modified in January 1995 and is now in use in the 8 Environment Agency regions. Before this the NRA reported pollution incidents, but within different operational areas. In some cases the boundaries of reporting responsibilities are immaterial as the incidents are grid referenced, but where data are summarised or the method of incident categorisation is changed, the resultant statistics can become meaningless. Before 1988, incidents were assessed against different criteria, primarily relating to agricultural pollution (Environment Agency, 1997a).

Annual summaries of water pollution incidents are published by the Environment Agency (e.g. Environment Agency, 1996; 1997a) describing in detail the regional and temporal trends in pollution incidents. The source and severity of incidents are described along with case study examples of incidents attended by Environment Agency staff. In an effort to indicate the general patterns of recent change in pollution incidents with reference to their potential impact on water supplies, the source of all Category 1 (major) incidents between 1990 and 1996 (inclusive) are summarised below (Figure 2.9). Since 1990 all substantiated pollution incidents have been categorised on the basis of their severity. Category 1 incidents are the most serious and involve one or more of the following:

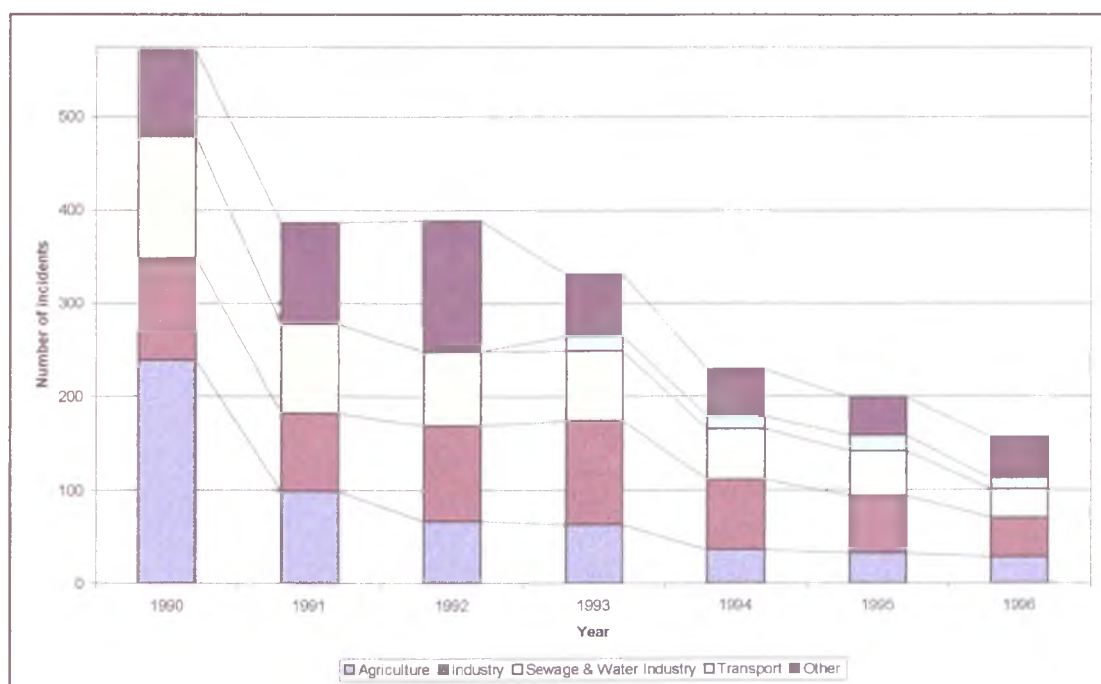
- a) *the closure of a potable water, industrial or agricultural abstraction point;*
- b) *an extensive fish kill;*
- c) *potential or actual persistent effect on water quality or aquatic life;*
- d) *investigation of extensive remedial measures;*
- e) *excessive breach of consent conditions;*
- f) *significant adverse effect on amenity value;*
- g) *significant adverse effect on a site of conservation importance.*

(Environment Agency, 1997a, Appendix A)

With the potential to close potable supply abstraction points it is these incidents that are of most interest to surface water intake managers and hence the assessment of risks to an intake site.

Whilst the total number of all reported pollution incidents has increased steadily since 1981, the number of substantiated Category 1 incidents has declined dramatically since they were first distinguished in 1990 (Figure 2.9). Of the 20,158 substantiated pollution incident reports in 1996, 156 were confirmed as Category 1, compared to 28,143 substantiated pollution events and 571 Category 1 incidents in 1990 (Environment Agency, 1997b).

Figure 2.9 Total number of Category 1 (major) substantiated pollution incidents by pollution source (1990-1996)

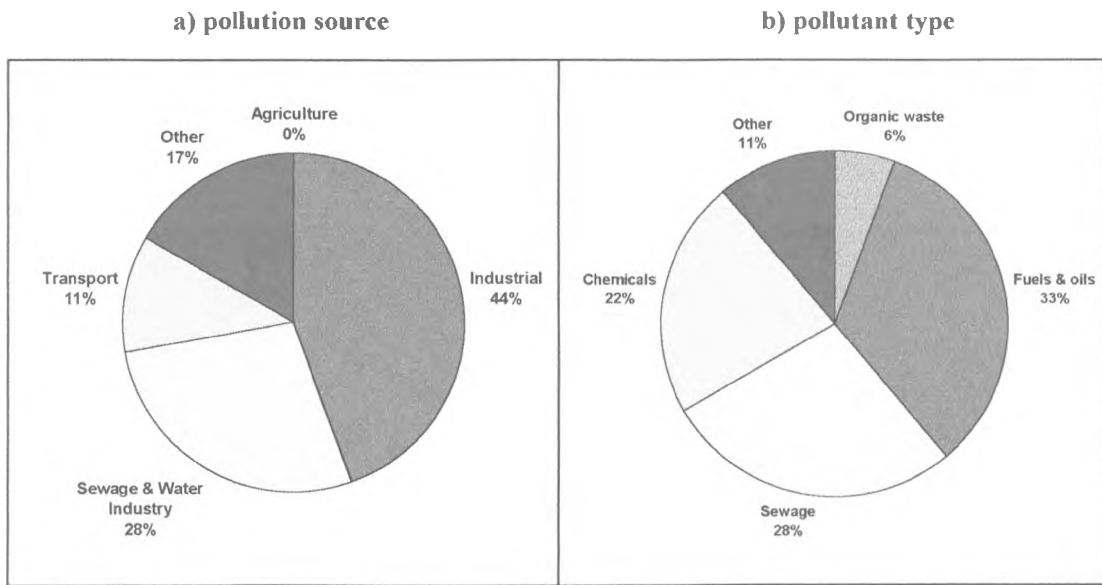


(Source data from: Environment Agency, 1997b)

In 1990 the most significant source of Category 1 pollution incidents was agriculture accounting for 42% of occurrences. In contrast, agriculture accounted for just 18% of Category 1 incidents in 1996, with industry causing the most incidents (27%). Over 500 of the incidents caused by industry resulted from construction activities. In response the Environment Agency is conducting a number of joint initiatives with the Construction Industry Research and Information Association to minimise pollution risks from construction activities (Environment Agency, 1997a). The proportion of incidents resulting from the activities of the water industry themselves (including sewage discharges) declined dramatically between 1995 and 1996 (from 20% to 15.5% of all incidents), illustrating increases in the performance of companies following improvement programmes enforced since privatisation (many of which were completed in 1995) and in the face of increasing legislative and consumer pressure.

Transport was first reported as a separate category in 1993, before which it was incorporated in the 'Other' category for reporting purposes. The number of transport related incidents has increased between 1993 and 1996, although the number of those classed as Category 1 fell by 25% in 1996. Of the transport related Category 1 incidents reported in 1996, 75% were the result of road transport, indicating the potential impact of road networks on watercourses. Of the 43 'Other' incidents classed as Category 1 in 1996, 36 could not be traced or classified by source, with the rest coming from residential / domestic sources, landfills, educational establishments and crown exempt properties (Environment Agency, 1997a). The type and source of the 18 Category 1 incidents occurring in the Environment Agency's North East Region (which contains the YWS operational area) during 1996 are shown in Figures 2.10a & 2.10b.

Figure 2.10 Category 1 (major) substantiated pollution incidents in the Environment Agency North East Region during 1996 by:



Source: Tables 4 & 5, Environment Agency (1997a)

Figure 2.10 a) shows that 44% of incidents that could potentially cause an intake to close resulted from industry and no such incidents occurred as a result of agricultural activity. However, within upland water supply catchments there are seldom large industrial sites, and agricultural activities have been known to cause intake closures in the past. The prevalence of industrial pollution may be because the North East Region of the Environment Agency includes large industrial sites in the lower reaches of major rivers and coastal estuaries.

Over one quarter of the Category 1 incidents were caused by sewage pollution or the activities of the water industry themselves. Some 68% of these were the result of surface water outfalls, combined sewer overflows, foul sewer systems and sewage treatment works. Water treatment works and water distribution account for only 13% of Category 1 incidents (4 events) during 1996. Over half of pollutants were fuels & oils or chemical in nature, probably originating from the high number of industrial polluters in the region, and pollution by transport accidents. A number of large pollution events were caused by vehicles falling directly into watercourses as a result of a road traffic accident.

Although these incidents are the most serious category of pollution and therefore have the greatest potential impact on surface water intakes, Category 1 events accounted for just 1% of the 20,158 substantiated pollution incidents in 1996. Less severe, but more frequently occurring pollution incidents may have a major impact on smaller watercourses, or have particular significance for an intake site. The importance of such events must therefore be considered on a local, not regional or national, scale. For pollution incident data to be used directly in risk assessments, catchment specific data should be obtained, preferably for a period of several years. Such information is not as freely available as the national trends reported above, but is preferable to avoid mis-representation by data that have been summarised over large spatial and temporal scales. The potential of catchment specific pollution incident data is discussed further in Chapter 6.

2.5 Potable water supply protection

2.5.1 A brief history of water supply protection

The need to protect drinking water has long been recognised. Coagulation and filtration have been in use as water treatment processes since at least 2000 BC (McGhee, 1991) and it is thought that the Romans brought laws on river protection with them when conquering England. The Magna Carta (signed in 1215) also included legislation to prevent the pollution of rivers (Keller & Wilson, 1992).

Contaminated drinking water can originate from one of two sources, either a problem with the quality of the original resource, or a problem that has resulted from the treatment and distribution of the drinking water. The approach taken to the protection of drinking water quality has turned full-circle in the UK during the last two centuries, from initial catchment protection measures, through the re-active 'treat everything' stage, and recently back to the more pro-active resource/catchment control approach (Newson, 1992).

Early water supply systems were protected through the confinement of pristine catchment areas (McDonald & Kay, 1988). At this time the municipal authorities supplying drinking water owned, or at least had some control over the water gathering grounds. Initial protection was through the exclusion of polluting activities from these gathering grounds. However, increasing industrialisation placed greater pressures on the integrity of these catchments and in the early 1800s drinking water abstraction sites were frequently downstream of industrial and sewage discharges (Keller & Wilson, 1992). The ownership of catchment areas also shifted from the public / municipal domain into private hands. The relationship between polluted water supplies and disease transmission was established in the nineteenth century and filtration and chlorination practices were introduced soon after (McDonald & Kay, 1988).

This was the beginning of the 'fire-fighting' era of UK drinking water quality control, where problems with water quality were increasingly 'engineered-out' of supplies using ever-improving treatment technologies. As new technology and processes were developed and supply organisations were able to utilise poorer quality resources, a more re-active approach was taken to quality protection. Modern treatment technologies combine processes such as microstraining, coagulation, flocculation, filtration, chlorination and ozonation. These are capable of removing particulate and suspended solids and bacteria and are often combined with tertiary treatments such as granular activated carbon (GAC). GAC works by absorbing organic molecules onto the surface of the granules, thus removing complex organic compounds such as pesticides, phenolic compounds and solvents that may cause taste and odour problems in the finished water (McGhee, 1991; Gray, 1994; Schofield, 1995).

In recent years there has been increasing pressure for supply companies to avoid water quality problems in the first place rather than reacting to incidents by treating the contaminated water. This is partly due to pressures of operating as private companies, where the water undertakers are now striving to balance the demands of shareholder, regulators and customers. Pro-active pollution prevention is not only seen as

pro-active environmental action (by both the regulators and customers), but can also reduce operating costs for example through a reduction in the use of coagulation chemicals, and is therefore financially beneficial for both customers and shareholders. The primary method of controlling the quality of the raw resource is through the pro-active management of the catchment areas. However, catchment management to protect raw water quality is no longer a relatively simple exercise of controlling access to land in the catchment as much of this is not now owned by the organisations collecting the water. The strategic management of catchment areas, through co-operative action with other organisations is therefore becoming increasingly common.

2.5.2 Catchment management

As described in Chapter 1, the catchment area of a river is an appropriate spatial unit for the study of water pollution issues. The management of these areas therefore provides the potential for the integration of land and water management activities to mitigate pollution risks.

Section 2.5.1 discussed the changing approaches to water supply source protection in the UK. This has been supported by a considerable amount of catchment based research investigating water quality issues. Catchment scale research in the UK, mainly catchment hydrology and process geomorphology studies began in earnest in the late 1960s. The main thrust of catchment research at that time was consideration of water quantity (Mitchell, 1991). Early studies such as Walling (1979) highlighted the influence of different catchment characteristics in discharge regimes and was typical of the water quantity bias to research at that time. Since then, a number of experimental catchment areas have been established in the UK, many of which are characteristic of the water gathering grounds of the Pennines and Wales (McDonald & Kay, 1988). Initially these were used in paired-catchment studies to investigate the impact of forestry on water yield, addressing the long running debate originated by the work of Law (1956). Work in small catchment areas during the 1970s and 1980s by researchers such as Walling (1974), Walling & Foster (1975), Foster (1978) and Walling & Webb (1981) reflected an increasing interest in the quality issues associated with catchment hydrology and land areas.

Empirical research such as that identified above has greatly increased the knowledge base of hydrological processes within catchments. More applied catchment scale research has also proved especially useful in water supply and quality management, with research findings often resulting in catchment management recommendations to improve water quality and yield. Boon *et al.* (1988), Kay & Stoner (1988), Newson (1988), Hornung *et al.* (1994), Mitchell & McDonald (1995), Heal (1996) and White *et al.* (1996) all studied relationships between catchment characteristics and water quality and Naden & McDonald (1989), Mitchell & McDonald (1992) and Heal (1996) investigated the predictive modelling of upland water quality based on land use distribution.

Hunter & McDonald (1991) investigated seasonal changes in the bacterial quality of water in upland catchments and Hunter *et al.* (1992) identified overland flow as the dominant transport mechanism for sanitary bacteria. Both these studies identified management options to reduce the contamination of water supplies, such as restricted grazing areas. Considerable work has been carried out into the discoloration of upland waters. The catchment scale application of the improvements in process knowledge resulting from this work is illustrated by Mitchell and McDonald (1995) in their proposals for catchment characterisation and hazard mapping to optimise water quality. Investigations into trace metal mobilisation have been carried out with reference to the potential impact on drinking water supply reservoirs (Heal *et al.*, 1995) and the impacts of acidification on metal releases, stream ecology and drinking water (Kay & Stoner, 1988). A review of contemporary water quality problems in upland catchment areas is given by Mitchell (1991).

A number of recent studies have attempted to quantify the effect of changing land use practices in catchment areas on water quality (e.g. Mattikalli & Richards, 1996, Johnes & Heathwaite, 1997). Such studies have highlighted the potential of catchment scale land and water management to improve water quality. The findings of many of these studies are used in this study and are therefore discussed in more detail in the following sections. Such catchment scale water quality research has enabled a move from site-specific investigations and allowed synergistic effects operating in catchments to be investigated (Mitchell, 1991). This in turn can improve the quality of the information available to decision makers in the catchment.

McDonald & Kay (1988) highlight some of the challenges initially faced when attempting to transfer the findings of objective scientific research to management decision making. However, recent moves towards more pro-active management of catchment areas has resulted in a transposition of research foci to more wide-scale, integrated approaches to catchment management, albeit based on the valuable empirical process knowledge gleaned from early catchment research. Werritty (1997) reviews the contemporary use of the term Integrated Catchment Management (ICM) throughout Europe and the world. Werritty (1997) considers 'integrated' catchment management to be the holistic management of a river and its surrounding catchment, with no one key issue having greater influence than any other over the management process. Gardiner (1994) described ICM using the following equation: $ICM \text{ or total catchment planning} = \text{Asset management planning} + \text{catchment management planning} + \text{Local Authority development plans}$. Thus, ICM involves the asset management activities of the water supply companies as well as the environmental, conservation and development plans of other stakeholders in the catchment.

Catchment management activities in England and Wales currently fall into two distinct categories of interest. Firstly, the formation of the National Rivers Authority (NRA) – now part of the Environment Agency (EA), separated the traditional roles of the regulator from the activities of the supply companies. NRA catchment management plans (and subsequent EA Local Environment Agency Plans) are not issued and any topics and recommendations discussed are intended to remain flexible to the needs of a particular catchment (NRA, 1995). The development of catchment-scale management plans by the NRA

and EA have therefore focussed on *catchment protection*, in terms of water quality and the environment as a whole. In contrast, the priorities of the water supply companies are water quantity, water quality and recreation and conservation, i.e. *catchment utilisation*. The water supply companies view of catchment planning is necessarily issue-led by the need to optimise water quality and yield, and has often resulted in the criticism of NRA catchment management plans as being too vague and inappropriate.

Supply companies are also keen to promote elements of the 'polluter pays' principle in which the control of problems at their source is preferable to treating the contaminated water (Breach & Porter, 1995) i.e. the cost of improving water quality is met by those polluting the water upstream rather than the companies who treat the resultant waters. The prevention of contamination at source can also reduce treatment costs and optimise catchment yield. In many cases this has prompted the water undertakers to take a more pro-active stance on catchment management.

Severn Trent Water Ltd. (STW) collect 65% of their raw water from river and reservoir catchments, many of which are located in upland areas of Wales and the southern Pennines. With such a reliance on catchment sources, STW is one of the most active supply companies in terms of catchment management. In particular, work has been carried out to reduce contamination from pesticides. This has involved pesticide use surveys, raw water sampling, catchment vulnerability studies, targeted catchment control measures and treatment of residual contaminants (Breach & Porter, 1995). The company has also prepared Catchment Protection Policy Documents for its supply catchments, identifying potential types of pollution hazard and providing advice to minimise the impacts of these. These documents can be compared to the general Guidelines for the protection of direct supply reservoirs and their gathering grounds produced by YWS (Yorkshire Water, 1992).

Breach & Porter (1995) stress the importance of combining treatment practices with catchment protection strategies to prevent contamination with pesticides as the impacts of catchment control take time to be realised. In some cases catchment control was not considered technically or economically viable. Where possible, catchment control has been found to reduce levels of pesticide in source waters and reduce treatment costs (e.g. reducing the frequency of GAC regeneration).

Within YWS, research into catchment control and management has been underway for many years. Much of the work by McDonald, Mitchell, Naden, Kay and Heal at the University of Leeds, mentioned above has contributed to the management activities of YWS. The publication *Guidelines for the protection of direct supply reservoirs and their gathering grounds* (YWS, 1992) describes the company's policies for protecting their raw water resources. These guidelines draw on the scientific research that has related catchment characteristics to water quality in order to optimise resources, but have been criticised for failing to attribute responsibility and accountability for the management actions required.

Much theoretical discussion has been undertaken in the academic community by authors such as Newson (1992) and Werritty (1997) about how catchment management planning should be conducted in an integrated and holistic manner. However, the primary concern of water supply companies is to optimise the yield and quality of water from a catchment area. This research therefore takes a narrower strategic planning approach as described by Mitchell (1990), but acknowledges the potential of broader-scale or holistic Integrated Catchment Management to bring together those stakeholders of relevance to the management planning process.

In developing a methodology for risk assessment this research may have the potential to aid in water company asset management planning and to combine this with innovative catchment management recommendations. The assessment of pollution risks to water supply intakes is an inherent element of catchment management planning for water supply companies for three reasons. Firstly, a primary concern is to reduce the risk of contamination resulting from activities within an intake catchment area. Secondly, much of the information required to carry out a risk assessment is collated in the catchment planning process. Finally, risk reduction can often be achieved through, or is dependant upon the management of the catchment area and therefore needs to be incorporated in the catchment planning process.

2.6 Summary and conclusions

Water companies need to comply with regulatory standards. In general, the performance of the 10 major water supply companies striving to reach the 100% level of compliance is improving. However, the pollution of raw water sources is still a major potential source of supply contamination and hence non-compliance. In the YWS operating region compliance failures have declined steadily since 1990 but common contaminants include pesticides such as PAHs, Isoproturon and MCPP. Impending changes to regulations increase the importance of this and mean that their approach to improving the quality of supplies must be flexible in order to incorporate any changes in legislation.

Numerous investigations into the quality of environmental waters in potable supply catchments have shown that many potential contaminants exists, and do in fact result in failures of the regulatory compliance of the abstracted water. There is therefore a need to gather information on the nature of pollution risks and the methodologies and approaches available for their assessment. National and regional trends in pollution incident occurrence have been discussed, with the need for the investigation of pollution events and pollutant sources to be studied on a local (preferably catchment) scale highlighted.

Catchment control is becoming increasingly popular as a method of optimising the use of raw water supplies and reducing treatment costs. Pro-active management activities have a positive environmental image, and have the potential to increase regulatory and environmental performance and returns for shareholders. Catchment management also embraces the concept of 'polluter pays' in that if water

industry managers can be informed of the sources of water quality failures they can (potentially) pass on some of the costs associated with the cleaning up of water to the initial polluters.

Considerable potential therefore exists for mitigating risks to drinking water quality through strategic catchment planning and the pro-active management of catchment areas. A consistent approach to identifying and assessing these risks on a catchment scale is therefore needed. In order to carry out such assessments, there is a need to store, manage and analyse large volumes of catchment data, primarily the spatial characteristics of the catchment. The use of automated techniques to manipulate and visualise such data will therefore greatly facilitate any risk assessment activity. As suggested by Rejeski (1993) it is proposed that geographical information systems have enormous potential to be used in such a role, a subject discussed further in the following chapter.

Chapter 3

Geographical Information Systems (GIS)

3.1 Introduction

This chapter introduces Geographical Information Systems (GIS) and discusses in section 3.5, some of their fundamental capabilities that may be of use in risk assessment studies. Initial applications of GIS by the water supply companies to asset management / facilities management (AM/FM) activities are described, as is the recent diversification of these into more strategic roles such as network management, leakage detection and control, waste disposal and the management of water gathering grounds. Examples are given describing applications in several water supply companies throughout the UK. The use of GIS by the regulatory bodies in the water industry is also considered, highlighting the variety of potential applications of GIS in water resource management. GIS have been widely used in the prediction of water quantity and quality and the prediction of non-point source pollution is of particular interest to this study. The current state of research in this area is discussed, with particular reference to issues affecting drinking water supplies in the UK. Finally, the use of GIS in environmental risk assessments is summarised, highlighting some of the potential applications of GIS in pollution risk assessment.

3.2 An introduction to GIS

An information system is a computer package that holds information about a particular subject. For example, a bank's information system may contain information concerning customers' names, addresses and account balances, all of which are linked by an identifying code. Brookes *et al* (1982) state the following key attributes that are required in an information system:

- decision oriented reporting
- effective processing of data
- effective management of data
- adequate flexibility
- a satisfying user environment.

A geographic information system (GIS) is a particular type of information system that is applied to geographically referenced data. Data can be stored within the GIS in a number of formats or data models. The most commonly used are vector (points, lines and polygons with attributes) and raster (gridded cells with associated attribute data). Most GIS contain an electronic system of maps that show locational and spatial relationships and a series of tables. These tables, usually in the form of a database, contain attribute data that describe the characteristics of each spatial entity. For example, the diameter of a particular pipeline or land use of a grid cell. Each feature in a GIS has a unique spatial location specified

by its co-ordinates and an identifying number that relates it to the attribute data in the database. The maps and database can usually be explored using a standard query language (SQL) or menu selection. The results of such searches can be displayed as database records or in the form of a map, enabling data attributes to be clearly represented.

The UK Department of the Environment define a GIS as:

"... a system of capturing, storing, checking, manipulating, analysing and displaying data which are spatially referenced to the Earth."

(DOE, 1987, Appendix B)

whilst Cowan (1988) places more emphasis on the problem solving abilities of the GIS, by defining one as:

"... a decision-support system involving the integration of spatially referenced data in a problem-solving environment."

(Cowan, 1988, p.2)

In essence, a GIS is a computerised system of storing and analysing spatially referenced data. The idea is by no means new, people have been combining and analysing mapped data for thousands of years, but it is the ability of a GIS to handle massive volumes of these data that makes the concept so valuable to geographical studies. Unlike paper maps, GIS data are not static in time and can be updated to represent changing conditions in an environment. As well as containing the required data, a GIS should include a range of functions that enable problem solving information to be obtained from the raw data. It is this functionality that provides the potential for application to risk assessment studies.

In order to expand the functionality beyond digital representations of paper records, a number of tools within a GIS enable the data to be manipulated, updated, integrated and queried to create new or redefined information from the original data components, thus 'adding value' to the original data. Common tasks that can be carried out in most commercially available GIS include geographic navigation and location or attribute based selection (e.g. all grid squares with attribute X, or of size Y). Geographic selections based on one map layer's geographic location with respect to another are also commonly used (e.g. selecting all the records from a soil map where soil A is WITHIN catchment area B). Other simple tasks used include measuring distances and areas and buffering around points or line features (e.g. defining a 10m floodplain either side of a linear river feature).

More complex geographical analysis available in GIS include map algebra or overlay, essentially combining the attributes of two or more data layers depending on their geographic location. These can be classified into two types of overlay describing the way in which map attributes can be combined - logical and arithmetic.

Logical overlay (e.g. AND, OR) is suitable where map attributes are represented on a nominal (e.g. soil type, land cover type) or ordinal (e.g. data ranked from poor to excellent) scale, e.g. Select areas where soil = winter hill AND slopes <5 degrees OR land use = burning. Arithmetic overlay (e.g. addition, subtraction) should be used where map attributes use an interval level of measurement. (e.g. grazing density, rainfall) and can be combined arithmetically. The use of both logical and arithmetic overlay is potentially powerful for representing the logical processes described in a risk assessment (see Chapters 4 and 5) and describing the hydrological processes operating in a catchment area.

It is possible to combine ordinal and nominal data arithmetically by scoring and weighting map attributes before adding or multiplying. Scoring takes place within datasets, and must be on a consistent scale in order not to adversely affect the weighting, i.e. all maps should be scored 1-5 or 1-3, but not a mix of both. The scores should, as far as possible, attempt to represent the interval (or ratio) level of measurement. Weighting takes place between datasets to represent relative importance. These weights have to be correct relative to one another, i.e. if criterion A is twice as important criterion B then weights of 1 & 2 or 2 & 4 are appropriate. Percentages can be used for simplicity. Such weighting can often require the use of expert knowledge or subjective decision making.

GIS can also be used to interpolate between data points to produce isolines or surface areas, or can be combined with mathematical models. Here the GIS can be 'coupled' to the model, providing input data, analysis and output display as necessary or, in some cases, models can be run directly within the GIS software.

The complexity of these analysis and display functions has often meant that GIS are implemented in businesses much more slowly than other information systems (Parker, 1996). The rise in popularity of user-friendly desktop mapping and PC-based GIS has largely eradicated such problems, with GIS software increasingly moving from UNIX and mainframe environments to the more familiar PC and Microsoft Windows based operating systems. Thus companies are increasingly able to provide powerful analysis and display capabilities to large numbers of non-specialist users across computer networks.

The capabilities of GIS such as those summarised above, to store, manipulate, analyse and display data have great potential for assisting in risk assessment studies (Rejeski, 1993). In order to investigate the potential for their use in water supply pollution risk assessments it is necessary to understand the current availability, capabilities and status of development of GIS within the water industry and how GIS have been used to assist in similar applications in the past. The following sections therefore present a review of these subjects.

3.3 GIS in the water industry in England and Wales

GIS technologies have been in use throughout the whole of the UK water industry for a number of years. The current structure of the water industry within England and Wales (as described in Chapter 2) has led to the diversification of GIS applications between the water supply companies and the regulatory bodies.

3.3.1 GIS in the water supply companies

Water supply companies in England and Wales have generally adopted a cautious approach to GIS implementation. Initial experiences of GIS for many water companies has been through the digitising of pipe networks, primarily utilising the software for digital mapping and asset management / facilities management (AM/FM) purposes (Martin & Taskis, 1993; Birkin *et al.*, 1996). This has also been found to be true of businesses in general in the UK, as described by Clarke *et al* (1993):

“GIS applications [are] mainly used in AM/FM - type applications as opposed to more substantive areas such as strategic planning”

(Clarke *et al*, 1993, p.326)

Since the privatisation of the water industry, supply companies have been attempting to balance the pressures from shareholders, regulatory, environmental and customer expectations. This has largely been approached through a re-engineering of the business as a whole. This rapid re-development of the companies' structure has gained particular benefit from an increased use of Information Technology (IT) systems (Cunningham & McGowan, 1994; Ray 1996). The generic ability of GIS to handle spatially registered data has enabled companies to take an integrated approach across the entire corporate structure. For example, under the 1989 Water Act, water service companies have a statutory obligation to maintain a register of their surface and underground assets. GIS and digital mapping technologies have obvious benefits in capturing and maintaining accurate information on asset location and attributes, and most of the water and wastewater utilities have invested heavily in capturing data on their distribution networks in digital form (Elkins, 1990; Hurst, 1996). These data are usually stored as vector features within the GIS. The benefits already identified in water industry applications include the ease of updating, display and creation of timely formal reports and hard copies, and the increased durability and accessibility of data (Martin & Taskis, 1993; Ray, 1996). This has enabled water service companies to comply with their statutory obligations, both for asset registering and textual reporting. Real improvements in business efficiency and customer service have also been realised as a result of computer-based AM/FM activities (Osbourne, 1991; Walton, 1996).

Within YWS the capture of the water supply distribution network has led to the development of a dedicated GIS-based system for asset information storage. The Water Network (Enquiry) Records System (WNETS) based on WINGS GIS contains data on pipelines and other assets describing their geographic location and various attributes such as pipe diameter, construction materials and age. Network data are represented at various scales from the region-wide “Yorkshire Grid” system down to the smallest manageable discrete unit of the distribution network which is a leakage control zone (LCZ).

Each LCZ supplies on average about 2000 customer properties. The water networks within adjoining LCZs are connected to each other across boundary valves. These valves are the means by which an individual zone can be isolated and disconnected for maintenance or operational management (Boulby, 1995). Unique logon scripts enable users to isolate sections of the network and to edit or update feature locations and attributes.

The use of GIS for the capture, storage and display of digital network information is essentially pure digital mapping and as such only utilises a small proportion of the potential functionality of most GIS. AM/FM activities in themselves therefore fail to explore the 'added value' that can be obtained from the vast amount of spatially referenced data held by the water supply companies (and their regulators). As the extensive network data capture exercises have come to an end, both the end-users and decision makers have begun to explore the more advanced spatial analysis potential of GIS to assist in operational activities. The increasing pressures on water supply companies to operate efficiently as private companies has led to many companies developing long term strategies for their IT departments, including the development of GIS systems beyond AM//FM applications to more pro-active uses such as the management of distribution systems. Such systems are becoming more widespread as a result of the rapid advancement of computer hardware and GIS software technology, as well as the increased storage and use of digital records of network assets (see for example, Ray, 1996).

A common strategic application of GIS is the management of the distribution system. Distribution network performance optimisation has parallels with the emergence of hydrological modelling (see Section 3.4) in that its emergence has taken place in two ways, though the direct development of dedicated GIS software applications with modelling capabilities, and by coupling network modelling packages to GIS reporting and user interface facilities.

Birkin *et al.* (1996) describe a GIS-based network optimisation software package developed for YWS. GRIDNET is a decision support software, enabling users to specify the characteristics of water sources and treatment works and run various scenario models using a 40 year historical rainfall dataset. The objective of the GRIDNET software is to optimise operating costs of Yorkshire Water's grid network through the integration of four modules; a reservoir simulation model, a pumping station model, a treatment works model and a network optimisation model. Using GIS-based high quality graphics and data storage, GRIDNET can simulate the effects of changes in operational procedures (including leakage control strategies and forecasted changes in demand), climate change and the impacts of catchment management. The full functionality of GRIDNET is discussed by Birkin *et al.* (1996). This software has recently been superseded by the Water Resources Allocation Package (WRAP) software.

Within Anglian Water Services Ltd., GIS software has also been used to integrate the network management activities with the specific aim of optimising performance and improving service to the customer (Anglian Water Plc., 1996; Ray, 1996). Anglian Water's records maintenance systems (RMS) contains a fully connected model of the distribution network, the ability to link customers and properties with the assets that serve them, as well as the functionality to be coupled to network modelling software.

This allows not only network data to be stored, but also the collection of information on network performance, with the potential to optimise distribution activities (Ray, 1996) and automate statutory reporting. Similar GIS technologies are in use within Thames Water Utilities where a GIS-based modelling and distribution management package is used, with particular emphasis on leakage detection and management. Digital information describing the distribution network is combined with computer-controlled valves and leakage detection instruments in the field to identify areas of potential low pressure or leakage. The system is used to analyse and display information on the distribution network, and has been found to be particularly effective in the communication of information to non-expert staff (Hurst, 1996). Less work has been carried out for the management of foul water systems using GIS. Although the digital asset information has been extensively captured using GIS by water service companies, these data have not been combined with the computer-based design and modelling common in the initial design and management of such systems.

More recently, GIS have been applied to customer information management such as billing, metering and complaints. North West Water Ltd. (part of United Utilities) has implemented a corporate wide GIS that enables business units to interact across the different functions of the organisation. For example, customer services representatives can identify the precise location of a customer's address, as well as access information on work schedules, planned interruptions to supply, water quality and forthcoming investments that may impact a customer's supply or are in geographical proximity to the customer's address all as a result of the implementation of the GIS (Cunningham & McGowan, 1994; Walton, 1996). Following the advent of GIS, such information can be accessed in a matter of seconds when a representative is responding to a telephone enquiry from a customer or other member of the public (Walton, 1996). Similar systems, also based on GIS (but not necessarily the same software) are in operation in most of the water service companies in the UK (see for example, Murphy, 1994; Ray, 1996; Fanner, 1997), and utilise GIS technology to directly benefit customers. Fanner (1997) also describes Bristol Water's plans to use their GIS to relate customer complaints about water quality to samples taken and logged in the field. This application has the potential to optimise not only the supply quality, but can assist in the management, scheduling and prioritisation of monitoring activities to suit operational and legislative requirements.

As briefly mentioned above, the water companies' statutory reporting obligations have also been addressed using GIS technology. Ashton (1992) describes how drinking water quality information from North West Water's archive was incorporated into SPANS GIS to facilitate the preparation of reports on compliance rates for supply zone quality. Again such systems are in use throughout the various water undertakers to monitor regulatory compliance. GIS have also be used in water supply companies to assist in the reporting of water pressure levels (Ashton, 1992), leakage (Hurst, 1996 – described above), the incidence of sewer flooding (Mitchell, 1997b), work scheduling, investment planning and design schemes for new developments (Walton, 1996) and pipe rehabilitation planning (Kingdom, 1991).

Along with more strategic applications such as network management and demand forecasting discussed above, GIS have been used to assist in the environmental and conservation management activities of water undertakers. Some examples of these long term planning applications of GIS technology being developed by WSCs are described below.

The Water Industry Sludge Disposal Optimisation Model (WISDOM) has been developed by WRc to address the increasing need to find alternatives to disposal at sea for sewage sludge. WISDOM, which is in use in the majority of the UK water service companies, combines hydrological buffer zones and crop census data in a GIS environment to assess the suitability of areas of agricultural land for sludge disposal (Woodrow, 1993). The Soil Survey and Land Research Centre's Land Information System (LandIS) has also been used to assess the suitability of land for sewage sludge disposal (Hallet *et al.*, 1996).

YWS have several custom built GIS applications based on the WING GIS to facilitate operational management beyond simple asset registering. The GISLAB application is based upon WINGS and incorporates a wide variety of spatial datasets. It is being used to demonstrate the power of GIS for YWS but not necessarily within the context of the water distribution network. Typical data loaded into the system include underlying geology, soil, rainfall, land cover, terrain contours, reservoir catchments and river networks and catchments. The recent development of GISLAB has been combined with an increase in the GIS functionality available within WINGS (Foster *et al.*, 1997) and the use of other GIS software such as MapInfo by external consultants. This includes the development of facilities for polygon algebra and rudimentary data modelling. Users will soon be able to manipulate and convert between raster and vector datasets. The amalgamation of the GISLAB data and the improved functionality are seen as key elements in the development of sophisticated GIS-based tools to assist in the integrated management of assets such as groundwater, reservoirs and river catchments - the primary sources of Yorkshire Water's feedstocks. The GISLAB application, its data holdings and the potential for use in pollution risk assessment is discussed further in later chapters (a summary can also be found in Foster *et al.*, 1996)

Collaborative research between Severn Trent Water Ltd. and the Soil Survey and Land Research Centre (SSLRC) has led to the development of a catchment scale information system for the management of water resources. The Catchment Information System (CatchIS) combines environmental modelling and GIS technology to optimise catchments for the purposes of the water company. The system, based on the APIC GIS combines datasets describing aquifer, catchment and sub-catchment boundaries, river networks, abstraction sites, land use, soils, agroclimatic data and information on pesticide compounds. Models of organic pesticide attenuation are linked within the system to assess the vulnerability of aquifers and surface waters to contamination by applied pesticides (Court *et al.*, 1995; Hallett *et al.*, 1996).

CatchIS is designed for use in the strategic and operational management of water resources in the Severn-Trent Water Ltd. operational area and supports the company's research into the control of pollution by catchment control (Breach & Porter, 1995; Court *et al.*, 1995) discussed in Chapter 2.

Similar collaborative research is underway between the University of Leeds and YWS. This work is focussed on the development of GIS-based tools that can be generically applied to catchment areas for management purposes (Smith *et al.*, 1996). The research considers 13 key catchment issues, relevant to many of the UK's upland water gathering grounds. The custom-built GIS-based application, designed to facilitate catchment planning for supply companies works on two levels. Firstly it operates as an inventory of catchment information, describing the physical characteristics of a catchment area and planning designations within it. Secondly the system supplies decision support for the long term management of the catchment, by performing predictive scenarios and modelling the effects of changing land use. The catchment management plans resulting from the systems should be appropriate for the supply company's response / input to Local Development Plans and the Environment Agency's Local Environment Actions Plans (LEAPs). Many of the features of this system have been developed alongside this research. Such collaboration has enabled fundamental elements of risk assessment to be incorporated in the system and this has ensured generic principles have been maintained in the development of this methodology.

With the major costs involved in the establishment of a corporate-wide GIS being dependant largely on the hardware selected and the geographical size of the operating area, the smaller water supply companies have also been able to exploit GIS technologies due to lower initial start-up costs (associated with the need for less extensive geographical data coverage). An example of the use of GIS within a small water supply company is the South Staffordshire Water Incident Management System (SSWIMS), used to provide vital information on underground leakage (Anon., 1996). Again the initial use of this GIS was for the storage of asset information, but recent developments in engineering knowledge and the software itself have enabled thematic mapping to identify potential leakage problems. Reported bursts are plotted in the GIS and correlated against the information on pipe composition and age from the digital network data, and the surrounding soil type. These data are then combined with results of laboratory testing on pipe integrity and used to predict potential future bursts and prioritise the company's future mains rehabilitation work (Anon., 1996). This again illustrates the potential added-value that can be achieved through the integration of various data within a GIS, and the benefits for strategic planning and business management even for a small supply company.

The commercial benefits of the utilities' large investment in IT, and GIS in particular, are substantial. Both Mitchell (1996) and Uff (1996) highlight the importance of dedicated GIS applications during the 1995 drought in the Yorkshire region. Ray (1996) estimates an annual saving resulting from the network management strategy of a round £3 million for Anglian Water Services Ltd., whilst Hurst (1996) predicts a saving of 200 resource years of effort in leakage reduction alone as a result of the improved network management afforded by the adoption of a GIS. Such savings have been an important element in securing the necessary investment in GIS and have helped produce operational efficiencies and improve levels of customer service throughout the industry. Greater potential benefits, through the development of new applications will continue to improve business efficiency, especially as long term planning and management tools are developed.

3.3.2 GIS in the water industry regulators

In contrast to the water supply companies, GIS applications in the organisations regulating the water service companies have, due to their different responsibilities, concentrated less on asset information capture and more on specific applications to address problem issues. Annand (1991) highlights the difference in scale between the locally-based asset management requirements of the former water service companies and the regional overview requirements of the regulators. Chapter 2 identified a number of organisations regulating the activities of the water supply companies. Of these, the Environment Agency (formally the National Rivers Authority, NRA) makes the most frequent use of GIS technology, although as identified below, this use is not as extensive as in the supply companies. No published work describing the use of GIS by OFWAT, the DWI or UK Government agencies (impacting directly on the water industry) can be found

In 1990, the recently established NRA found that the software skills, requirements and areas of application of GIS products by their staff varied greatly from area to area and between operational regions. A national strategy was therefore developed in order to integrate activities across the organisation and provide a common GIS base for the future. This was planned as the Water Archive and Management System (WAMS), that was to provide all the functionality required of a GIS utilising the Authority's vast (and varied) databases and responding to all their spatial analysis queries (along with other textual and graphical reporting). However this was found to be far beyond the capabilities of the technology available at that time and the original specification could not be met by the IT providers. Hence, no national or regional strategy for the integration of digital data in the Environment Agency is currently in place. Instead, small specialist teams of GIS expertise have emerged throughout the Agency, often responding to individual project needs. Annand (1991) states that 13 small scale GIS projects were implemented throughout the NRA during its first year of operation.

One of the largest applications of GIS within the NRA was the system developed in the Anglian region. Dowie (1993) identified three areas of application to the operational activities of the Anglian NRA. Firstly, as a mapping tool the system provides 1:50,000 scale maps of features such as flood areas, Sites of Special Scientific Interest (SSSIs) and aquifer outcrops. These were used in the NRA's role as a statutory consultee on planning applications.

The storage and updating of these digital data has resulted in considerable savings in the costs associated with map and hard copy production (Dowie, 1993). Secondly, the GIS has been used as an operational tool. Within the Planning Liaison section the Authorities response to planning applications is co-ordinated spatially by the GIS. Staff whose areas of responsibility fall in or near the site of a planning application are automatically consulted as part of the Authorities official response to the application. Dowie (1993) estimates a saving of three to four person-years per annum as a result of this automation. Thirdly, the GIS has been used as a strategic tool within the Anglian region. The Shoreline Management Systems combines data from a number of organisations to provide information on flood defence works.

Specific information on defence works and work schedules can be combined with marine hydraulic models to facilitate and plan the comprehensive management of the shoreline.

Farthing & Stuart (1995) describe another localised application of GIS in the NRA, this time in the Thames region. Like the Anglian region, Thames inherited some GIS expertise from the Regional Water Authority (Annand, 1991). Farthing & Stuart (1995) used SPANS GIS in a pilot study to model the hydrological response of river catchments. This involved combining the stream networks with digital sewer records and elevation data to predict the time of travel of storm waters and river levels. This information is then used in commenting on plans for floodplain and land development (another statutory responsibility of the NRA) illustrating how two applications were independently developed for similar uses in two different NRA regions.

Fletcher (1993) describes the use of GIS and remotely sensed images in the Severn Trent Region of the NRA. Again this project began as a small-scale investigation, looking at nitrate contamination of groundwater (using SPANS GIS). As the potential of GIS was realised and demand increased, the project expanded to enable region-wide assessments of groundwater contamination (based on geology, groundwater catchments and cropping patterns). Fletcher (1993) anticipated future work investigating pesticide runoff and leaching, highlighting the divergence of regulators' activity from the asset management of the water supply companies, but little published work has been forthcoming.

GIS applications such as those described by Dowie (1993), Fletcher (1993) and Farthing & Stuart (1995) remain rare, despite potential for integration and development following the formation of the new Environment Agency, due to a lack of any national or regional strategic plan for GIS operating environments and software. One exception to this apparent lack of direction is the National Groundwater Vulnerability Maps for England and Wales where national datasets have been combined to predict groundwater resources at risk from potential contamination. These maps are created by combining data describing soil and geological characteristics. However, this work was carried out by a specialist team working on a national data set with little integration of GIS activities between the NRA / Environment Agency regions during the project. A coherent national strategy is therefore required to harness the full potential of GIS for the broad spectrum of the Agency's responsibilities.

3.4 GIS and hydrological modelling

There has been a large amount of research into the use of GIS techniques for hydrological modelling in the prediction of both water quantity and quality. Traditionally, the fundamental limitation of hydrological modelling has been the spatial variability of hydrological data which has resulted in the simplification, or lumping of model parameters into average conditions. GIS have enabled the full spatial content of input data to be represented and adopted, allowing an increased use of distributed modelling techniques (Vieux, 1991; Spence *et al.*, 1995).

Three major areas of application of GIS to hydrological studies have been the inventory and assessment of existing hydrological data, the determination of hydrological parameters (for use in hydrological models) and the integration and coupling of GIS software with computer-based hydrological models (Maidment, 1993; McDonnell, 1996).

The majority of the modelling work (particularly three-dimensional prediction) has involved the investigation of groundwater resources and contamination, especially in mapping groundwater vulnerability (e.g. Barrocu & Biallo, 1993; Hiscock *et al.*, 1995; Tim *et al.*, 1996). Particular attention has been drawn to the percolation of water and pollutants to groundwater. Representing geographic space using three-dimensional grids (Tim *et al.*, 1996) or successively coarser grid enables increasingly complex subsurface processes to be modelled. However, the application of GIS to surface hydrology is of much greater interest to this study, particularly in the prediction of surface water quality. Studies of surface water quantity are of interest as they indicate the potential advantages and disadvantages of representing hydrological phenomena using GIS.

In studying surface water quantity, GIS have been used in all three of the application areas highlighted by Maidment (1993) and McDonnell (1996) and identified above. The display capabilities of GIS enable the clear visualisation of hydrological data, which has been found useful in the communication of temporal changes in flood inundation (e.g. Farthing, 1994; see also Section 3.5).

GIS are widely used in the determination of input parameters for hydrological models of surface flows. Indeed, McDonnell (1996) considers such applications to be one of the most active areas of contemporary research. Hogg *et al.* (1993) and McCormack *et al.* (1993) describe the use of digital elevation models (DEMs) within GIS to identify hydrological catchment boundaries and feature characteristics such as drainage areas, stream lengths, stream slopes and discharge estimates. Such variables can then be input into process response models for hydrological forecasting. Vieux (1991) describes various examples of GIS used to obtain the input data for both water quality and quantity models, including the provision of input parameters for a distributed finite element model to predict overland flow from the ARC/INFO GIS software. Romanowicz *et al.* (1993) used GIS data to predict soil moisture input values for TOPMODEL (Beven & Kirkby, 1979) and display the subsequent results, thus automating the modelling process.

Battaglin & Goolsby (1996) provide an excellent example of using GIS in hydrological parameter estimation. They use a variety of GIS procedures to extract physically based hydrologic response unit (HRU) parameters including area, mean elevation, mean slope, predominant soil type and predominant land cover type. Mean elevation is calculated from the arithmetic average of all DEM points within a grid square and the slope data derived from a triangular irregular network (TIN). Predominant land cover and soil types are determined by overlaying the relevant data layers within the GIS and carrying out geographical queries based on the HRU boundaries. A FORTRAN program was then used to convert the GIS output into a suitable format for direct input to the US Geological Service Precipitation Runoff Modelling System (PRMS). PRMS can be used to simulate stream flows and assess water resource sensitivity to climate change.

Whilst the above examples illustrate how GIS can be used in the extraction of data for input to water resource models, it is the use of GIS in the prediction of water quality that has the most potential to facilitate pollution risk assessment studies. Numerous studies have attempted to quantify pollution, and identify and prioritise pollution source areas using GIS. Such approaches have proved especially useful in the prediction of non-point source pollution. These have involved both the coupling of GIS to existing non-point source pollution models and the direct modelling of non-point sources within a GIS.

Tim *et al.* (1992) coupled the Virginia Geographic Information System (VirGIS) with simplified non-point source pollution models to predict soil erosion, sediment yield and phosphorus loading from a mixed agricultural and woodland catchment. Base data layers including soils, land use, elevation, watershed and administrative boundaries were manipulated in the GIS to create derived data layers used as the input parameters to the water quality models. These derived layers included slopes, erodibility factors and water quality and erosion indexes that were reformatted into matrices for input to the soil loss (SLOSS) and phosphorus yield (PHOSPH) models. The model results were then re-imported to the VirGIS for display and analysis.

The approach of Tim *et al.* (1992) maintained the geographical attributes of the input data, hence producing model results showing the spatial distribution of soil erosion, sediment yield and phosphorous loading across the catchment area. The results therefore have the potential to provide decision support for pollution monitoring and control programmes by prioritising geographical areas of the catchment for further action. Such an approach is ideal for integration with risk assessment studies as it could be used not only to identify areas of the catchment that present a pollution hazard, but also to recommend potential areas for risk mitigation measures to be applied.

PC ARC/INFO was used by Jankowski & Haddock (1996) to simplify the determination of input parameters and display the output results of the AGNPS (AGricultural Non-Point Source) model. Tim & Jolly (1994) conducted a similar study using ARC/INFO GIS and the AGNPS model to examine non-point sources of agricultural pollution in a river catchment. Again, the input parameters were extracted from environmental data within the GIS, run through the model and then re-imported to the GIS for

display and analysis. In addition, the GIS was used to predict the impact of land management strategies. The initial GIS data were modified to simulate the impacts of a proposed land management strategy and new input parameters for the model extracted. Reductions in sediment loads of up to 71% were predicted following the implementation of land management practices.

Yoon (1996) also coupled a relational database management systems to a GIS and non-point source model to assist in decision support. Best management practices were assessed using the predictive power of the GIS (through the amendment of the environmental data and subsequent input parameters) and reductions of 26% of current non-point source nitrogen and phosphorous pollution were predicted. Such approaches have clear potential for application to the investigation of alternatives risk management scenarios.

A relatively early study involving the modelling of non-point source pollution within a GIS (as opposed to coupling the model to the GIS) was carried out by Gilliland & Baxter-Potter (1987). They describe the use of the RGISM GIS to assess the non-point source pollution potential of three agricultural land uses (an animal feedlot, a pasture and a corn field). Three models were constructed within the GIS to predict pollution sources. Estimates of bacterial density were determined from the literature and assigned to land use classes within the study area. The Soil Conservation Service Curve Number (SCSCN) technique and the Universal Soil Loss Equation (USLE) were used to generate runoff and potential erosion estimates respectively. These results were combined with the digital soil maps within the GIS. The spatial extent of bacterial pollution potential, runoff and erosion could therefore be mapped using the data held in the GIS. Although the models were not calibrated by field studies (at the time of publication), Gilliland & Baxter-Potter (1987) identified the capability of GIS-based pollution potential (hazard) maps in communicating the geographical distribution of pollution source areas.

Hamlett *et al.* (1992) used a cell-based ranking model to predict the non-point source pollution potential of 104 watersheds across the state of Pennsylvania, USA. They derived an agricultural pollution potential index by combining four index values calculated in the GIS. The runoff index was determined from the SCSCN approach as in Gilliland & Baxter-Potter (1987), and the soil data layer and the sediment production index was calculated with a modified version of the USLE. Animal loading and chemical use indexes were calculated from agricultural census and land use data, combined with average production and usage rates. The values attributed to each index within a watershed were then combined to give the overall agricultural pollution potential rank for a particular watershed. The relative potential impact of the 104 watersheds could therefore be easily displayed in the GIS. Hamlett *et al.* (1992) provide a useful insight into the potential use of GIS-based ranking techniques to combine geographic data represented on varying spatial scales. They also utilised ranking to successfully combine nominal and ordinal data as discussed in section 3.2. A number of their approaches to ranking pollution potential are of potential use in risk assessment studies and are therefore referred to in later chapters.

The prediction of non-point source pollution potential has also been carried out for urban areas. Kim *et al.* (1993) predicted the contribution of heavy metals, phosphorous and sediments from sewershed areas. PC ARC/INFO was used to determine the contribution of pollutants from land use data, soil type, rainfall, and pollution control facilities. The total pollution loadings for each sewershed, calculated in the GIS by aggregating the loads of contributing areas were determined in order to prioritise pollution mitigation actions.

Poiani & Bedford (1995) review a number of GIS applications to predict non-point source pollution. They discuss both modelling within GIS and GIS coupled (linked) to external models. Although investigating these approaches from a wetland management viewpoint, Poiani & Bedford (1995) do highlight a number of pertinent characteristics of GIS-based pollution studies. They identify two drawbacks of conducting hydrological modelling within a GIS. Firstly the loss of temporal resolution and secondly the use of more simplified models (such as ranking and indexing) that primarily give qualitative results based on pollution potential. However, in a risk assessment context, such qualitative assessments are particularly useful for identifying areas of a catchment containing potential pollution sources or that warrant further investigation (thus linking with catchment management planning activities). Poiani & Bedford (1995) suggest that linked non-point source models and GIS offer the most potential for wetland applications as more complex models can be used. This has certainly been found in surface water applications where GIS have been used to provide increasingly accurate input data for existing models such as AGNPS.

From the investigation of existing uses of GIS in hydrological modelling it is evident that GIS have immense potential for facilitating the prediction of water quality in risk assessment applications through the automated representation of hydrological processes, or coupling with hydrological models. As noted above, qualitative assessments of pollution potential may be useful in the determination of catchment hazards, whilst hydrological parameters can be extracted for use in existing, or in the development of new models. The use of catchment characteristics to predict water quality, as described by Boon *et al.* (1988), Kay & Stoner (1988), Mitchell & McDonald (1992, 1995) and Heal (1996), lend themselves particularly well to integration with GIS. As such, the production of hazard maps suggested by these authors would also be greatly facilitated, as would the graphical communication of risks during a risk assessment procedure. Many studies, among them Tim & Jolly (1994) and Yoon (1996), have illustrated the ease with which the impacts of potential management strategies can be tested using GIS-based approaches. This predictive capability is another fundamental area in which GIS could be used to facilitate the risk assessment process in water supply catchments.

3.5 GIS and risk assessment

The previous sections have reported the use of GIS in management and hydrological applications. GIS have also been used to directly facilitate risk assessment, although rarely in the field of water quality. Wadge *et al.* (1993a) found GIS to be appropriate tools for the analysis of hazards and the assessment of risks as they have the ability to analyse spatial patterns, manage inductive and deductive modelling routines and calculate statistical probabilities. The visual display capabilities of GIS were predicted to play an increasingly important role in the communication of risk assessment findings by Rejeski (1993). Stein *et al.* (1995) provide a useful discussion of the use of GIS in environmental risk assessment, with particular reference to contaminated soils.

Common fields of application include landslide and subsidence prediction (Van Weston *et al.*, 1993; Wadge *et al.*, 1993b), seismic hazard prediction and sensitivity analysis (Emmi & Horton, 1995), the assessment of risks from transporting hazardous goods (e.g. Brainard *et al.*, 1993), flood risk assessment (Brimicombe & Bartlett, 1996) and groundwater pollution. A recent collection of papers describing the potential of GIS for application to risk assessments in some of these fields can also be found in Carrara & Guzzetti (1995), with further applications in Goodchild *et al.*, (1996).

Van Weston *et al.* (1993) used qualitative classification and ranking techniques and statistical analysis of datasets held within a GIS environment to predict landslide occurrence in the Cordillera Central of Columbia. GIS have also been used in the prediction of forest fire location (Chuvienco & Salas, 1996). The common approach to such assessments is to plot the location of historical events, and use the spatial analysis capabilities of the GIS to determine the environmental variables causing the problem. For example van Weston *et al.* (1993) used the deductive combination of digital datasets describing geology, topography, landslide history and land use within the GIS to create qualitative hazard maps and large scale landslide probability maps. The variables identified will necessarily be dependant on the data layers held within the GIS and consequently a certain amount of care, expert knowledge or previous investigation is required to select appropriate data. GIS software enables the analysis of numerous spatially variable data in a systematic manner, a task of immense proportions prior to the use of GIS. This has improved the understanding of the processes responsible for hazards and risk realisation, increased the objectivity of hazard predictions (van Weston *et al.*, 1993) and enabled pro-active risk management through the prediction of future events (Wadge *et al.*, 1993b).

Brimicombe & Bartlett (1996) combined the storage of drainage basin characteristics in a GIS environment with hydraulic modelling of flood hazard and risk maps. Data were stored and analysed in the GIS before analysis by the hydraulic modelling. Post-processing display of the hydraulic output data was combined with digital terrain models and land use data to identify areas of inundation (hazard maps). These were then combined with value damage estimates to produce flood risk maps. Decision support was provided by iterative applications of the model to modified GIS data, allowing the effects of land use change to be predicted.

Previous applications of GIS techniques to surface water quality have so far been restricted to the predictive modelling of individual parameters or non-point source pollution types (e.g. agriculture) such as the work described above and have not involved discrete assessments of the overall risk to drinking water quality from a source catchment area. No previous research has been carried out into the use of GIS techniques for the general assessment of pollution risks to surface water intake sites originating in the upstream catchment.

Whilst such applications may appear to have limited direct relevance to studies of drinking water pollution, the techniques used in the identification and assessment of hazards provide useful indications of the possible benefits of GIS. A specific aim of this research is to determine whether similar applications of GIS techniques can successfully be used in the assessment of pollution risks to drinking water supplies (Chapter 1).

3.6 Summary and conclusions

The discussion of a number of GIS applications currently in use in the UK water industry has shown that although initial applications were restricted to capturing digital information on the distribution networks (some of which is still underway) there is increasing exploration of more advanced spatial analysis using GIS to facilitate operational and environmental management within the water industry. Initially, such complex GIS applications were poorly received, but with increasing commercial pressures operating on the businesses and the development of such applications becoming more cost-effective and user-friendly, GIS are being used for ever more complex tasks. GIS technology has given water supply companies the potential to integrate many of their activities and share information across business functions, increasing the organisation's efficiency and levels of customer service. Risk assessment is another tool which can both provide enhanced operational information and will benefit from the application of existing GIS technology to optimise the flexibility and transferability of a methodology.

Recent developments in network optimisation tools, customer information systems and the creation of generic information systems to enhance the management of water gathering grounds (particularly on a catchment scale) are receiving increased attention from both water supply companies and the regulatory organisations overseeing their operations. New initiatives such as GISLAB potentially provide the data and functionality required for risk assessments within water supply companies. The potential applications of the data held within GISLAB (and the associated WINGS software) are discussed extensively in later chapters.

GIS techniques have been harnessed in all areas of hydrology in recent years and have proved particularly useful for obtaining input data to hydrological models. A number of water quality studies using GIS have been described and several potential applications in water quality risk assessment are highlighted. GIS also have the potential to integrate data using ranked datasets and be used in the predictive modelling of the impacts of risk management scenarios.

The application of GIS to environmental risk assessment have in the past been limited to geomorphological studies of landsliding and subsidence, the transport of hazardous materials, flooding and groundwater contamination. However, knowledge of the techniques developed in these GIS-based environmental risk assessments, when combined with knowledge of how hydrological processes can be represented using GIS, creates an information base from which a methodology for the assessment of surface water pollution risks using GIS can be developed.

The application of GIS-based risk assessment to surface water intake catchments has not previously been investigated and therefore provides immense potential for the development and application of a novel methodology. At a time when organisations across the water industry are beginning to appreciate and develop the potential of GIS technology, coupled with moves towards pro-active management of resources through the prediction and protection of problems, the formulation of a methodology to assess pollution risks in a water supply catchment which utilises the power of GIS to handle large, spatially referenced data is particularly timely.

Chapter 4

Hazard, risk and risk assessment

4.1 Introduction

The previous chapters have emphasised the need for a pro-active approach to assessing sources of pollution in supply catchments and the potential capacity of new technologies such as GIS to assist in these assessments. In this chapter, the theoretical basis of the risk assessment field is discussed. This knowledge is required in order to identify the strengths and weaknesses of existing methodologies, and to develop the framework of the methodology (see Chapter 5). The terms risk, risk assessment and risk management are defined, and the need for a generic structure for risk assessment methodologies proposed. The sociological dimensions of risk are discussed, and some initial ideas theorised but given the aims of this thesis (Chapter 1), it is beyond the scope of this research to investigate the sociological impacts of drinking water pollution in any great detail.

The purpose of this chapter is to discuss the fundamental principles governing a formal systematic assessment of risk, namely, what is meant by a 'risk' and how can risks be identified, assessed and managed to avoid potential loss to the human and physical environment. The definitions selected will influence not only what is identified as a risk, but also how the whole assessment process is carried out. It is therefore important to state clearly the intended use of the term risk prior to conducting an assessment. The chapter begins by discussing the definitions of the terms hazard and risk, and identifies the various types of risk before defining these terms specifically for use in this research. The frameworks behind common risk assessment procedures are described and the importance of risk perception and uncertainty identified.

The academic and commercial literature on the subjects of risk, risk assessment and management is extensive, not least because of the varied applications that they have in modern society. It is not intended therefore that this chapter will provide a conclusive review of the risk field. The themes outlined here are those that have direct relevance to developing and utilising a risk assessment approach to drinking water quality studies.

4.2 Hazards and risks

4.2.1 Definitions - hazard vs. risk

There are many interpretations of the term risk when it is applied to the environmental sciences. There is also considerable variation within the risk literature as to the meaning of terms such as hazard, risk, risk assessment and risk management. This is particularly so when the terms are exported from literature relating purely to the theory of risk to other scientific disciplines such as the environmental sciences. It is also partly due to the developing nature of the risk assessment field.

Despite variations in the interpretation of meanings, the term risk almost always refers to an adverse impact (for example, the loss of a human life) rather than a positive gain (such as increased life expectancy). The widely applicable basis is often considered to be one of the main strengths of risk-based approaches to environmental management (Gerrard, 1995). In an attempt to clarify the concepts involved in studies of risk and to subsequently define the term risk assessment for the purposes of this research, a discussion of these principles follows.

Many workers in the field of risk assessment define a risk purely in terms of the so-called 'Rio Definitions' that are incorporated in the EC Directive (93/67/EEC) resulting from the 1992 Earth Summit in Rio de Janeiro (EC, 1993). However, these were primarily intended to refer to chemical substances in the environment (Department of the Environment, 1995) and are therefore not appropriate for dealing with the wide variety of environmental risks that may affect water supplies. The terms risk and hazard are often used interchangeably (Jones, 1992), but it is useful in the present context to distinguish quite different meanings.

In its simplest form *hazard* relates to the property of a substance or activity to cause harm to man, the environment, property, or to cause economic loss (Gerrard, 1995). Investigations into the nature and characteristics of the substance or activity in question will afford an understanding of the hazard and this can then form the fundamental knowledge base for the risk assessment process. These investigations usually involve a combination of the study of existing scientific and empirical knowledge, experimental results and the 'expert knowledge' of the assessor. In the context of pollution hazards to drinking water supply intakes, information that could lead to the identification of such hazards may originate from records of river water quality, historical pollution records, field surveys of the supply catchments, examination of discharges to the river and consultation with the local authorities (Cole *et al*, 1988). These approaches are highlighted in later sections describing hazard identification and in Chapter 5.

In contrast to the definition of hazard outlined above, *risk* usually refers to a combination of both the frequency of a hazard occurrence and consideration of the effects or impacts of that occurrence. In attempts to formally define what is meant by the term 'risk' the UK Department of the Environment

follows the recommendations of the Royal Society who, in the seminal text describing contemporary theories of risk "Risk: Analysis, Perception and Management" define a risk as:

"a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequence of the occurrence."

(Royal Society, 1992. p.4)

Gerrard (1995) also defines risk in terms of both probability and consequence.

"the likelihood, or probability that a particular set of circumstances will occur, resulting in a particular consequence, over a particular time period."

(Gerrard, 1995. p.301)

Many formal definitions of risk, including those given above rely on the aforementioned definition of a hazard as being a property or situation that in particular circumstances could lead to harm, i.e. the loss of inherent quality suffered by a physical or biological entity (Royal Society, 1992; Department of the Environment, 1995; Gerrard, 1995). This consideration of both the probability and consequence of occurrence commonly used in the field of risk study is referred to by many as the *two-dimensional approach* and forms the basis on which many researchers, across the wide spectrum of fields that consider risks, formulate their initial definitions.

Whyte & Burton (1980) use a variation of the two-dimensional theme in that they consider the term risk to have two distinct meanings. Firstly, it can be defined as the potential or danger of something undesirable occurring. This definition is concordant with the more broadly accepted definition of a hazard, and highlights one of the many discontinuities that necessitate careful definition of these terms. Alternatively, they suggest that risk can be interpreted solely as the probability of this occurrence taking place. With this second approach, risk is defined purely in terms of a mathematical probability and does not take into account the ramifications of the hazard in terms of effects to man or the environment. However, many exponents of risk studies, including Whyte & Burton themselves, consider estimations based purely on probability to be meaningless (Kates, 1978; Whyte & Burton, 1980; Royal Society, 1992, Gerrard, 1995; Pollard *et al*, 1995) as such estimates show no consideration of hazard consequence.

Estimating probabilities can be very difficult, particularly if data are scarce or the area of application is new. Problems can also occur if purely probabilistic risks are considered under different scenarios. Taking the example of lightning strikes, certain people can be considered more at risk than others due to their location (e.g. golfers), and the effect on some members of society may be greater than others (e.g. people with heart conditions). It is therefore usual for the definition of risk to include some consideration of the *consequences* of a particular hazard. The *significance of these consequences* is usually used as an additional parameter to weight the probability values given to certain hazards, thus defining the risk. A consequence can be considered to be direct harm to humans or the environment, or an economic cost associated with such harm. Figure 4.1 shows general definitions of the terms hazard and risk, summarising the consensus of the literature referring to hazard and risk studies

Figure 4.1 General definitions of the terms hazard and risk

<p>Hazard:</p> <p><i>“the property of a substance or activity to cause harm to humans or the environment, or to cause economic loss”</i></p> <p>Risk:</p> <p><i>“a combination of the probability, or frequency of occurrence of a defined hazard and the magnitude of the consequence of occurrence”</i></p>

With respect to drinking water there are a number of regulatory controls on the quality of both raw water and treated drinking water (see section 2.2). A hazard is therefore the property of an activity or substance that influences the quality of the water during collection, treatment or distribution which may ultimately result in a regulatory failure of water quality at the tap. The consequence of a risk being realised can be considered in terms of the potential public health, legal and economic implications of a regulatory failure to supply wholesome water to consumers. The standards for the quality of drinking water are specified in the EC Drinking Water Directive (80/778/EEC) and subsequent UK legislation (HMSO 1989a). Financial and legal penalties resulting from regulatory failure will also affect the suppliers and should be considered in conjunction with potential public health impacts on consumers. The definition of these terms as they will be used in this research are given in Figure 4.2.

Figure 4.2 Definitions of Hazard and Risk for assessing pollution risks to public water supply intakes

<p>Hazard:</p> <p><i>“the property of an activity or substance that may adversely affect the quality of the drinking water during collection, treatment or distribution and which ultimately results in a potential failure of drinking water quality regulations at the point of supply”</i></p> <p>Risk:</p> <p><i>“a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the legal, economic and public health implications of this occurrence”</i></p>

4.2.2 Dimensions of risk

There are many different types of risk that potentially or actually exist. These can be identified by the nature of the risk e.g. economic risks, health risks, environmental risks, or by the potential receptors, for example, individual, societal and global risks. Every activity in daily life involves some element of risk, such as crossing the road, driving a car or contracting an illness. There can therefore be no such thing as zero risk (unless no activity takes place), although society often dismisses some risks as being trivial or acceptable because they are experienced often, or if they are rare and beyond the individual's control (e.g. a natural disaster). It is therefore important to consider the dimensions of a risk as this will impact how they are perceived and assessed.

In this study, environmental and health risks are the primary considerations, although these may have legal and financial implications for the water supply companies, resulting from a contravention of the water supply regulations. Discussion of risk assessment, management and perception is therefore necessarily biased toward environmental risks. Environmental risks are defined as hazards or dangers that have adverse, probabilistic impacts on humans or the environment and that either arise or are transmitted through the air, water, soil or biological food chains (Whyte & Burton, 1980). They can vary greatly in their characteristics and origins and commonly affect people who are unaware of their presence i.e. involuntary victims.

The significance of any activity that constitutes a hazard to health or the environment can be judged from an assessment of social acceptability. As discussed later, a risk may be considered more acceptable if exposure to the activity is voluntary (Fryer & Davies, 1995). In general the risk to human health from the contamination of drinking water can be considered to be involuntary. In the United Kingdom consumers have come to expect that the water supplied to their taps does not (as far as current laws and scientific knowledge suggest) present a threat to their health if ingested. The nature of some chemical compounds means that they may enter a water supply system in undesirable concentrations without being detected during the abstraction or treatment processes (see for example: Short, 1993; Whitworth, 1994; Foster & McDonald, 1996). If the supply company is unable to notify the consumers of a possible contamination of their supplies, then ingesting the water may present an involuntary risk to their health. Also, the monitoring of supply sources may be such that by the time samples have been processed and analysed, the potentially contaminated water will already be in supply. The first indication of a contamination often therefore comes from customer complaints (Jarvis *et al*, 1985).

Humans are exposed to hazards and risks every day, with the ultimate risk to an individual being death. Risks to individuals are usually expressed as the probability of death due to a certain event per year (Fryer & Davies, 1995). The ranking of activities using these probabilities can inform individuals of the potential risk involved in taking part in a particular activity, but the decision of whether or not to expose oneself to the risk is usually a personal decision based on past experiences and knowledge. It is often found that individuals will personally tolerate risks that they would not wish to see imposed on society as

a whole in order to achieve greater personal satisfaction, e.g. higher salaries, individual achievement. An individual's willingness to accept risk will also be influenced by whether the possible adverse consequences are immediate or delayed (Fryer & Davies, 1995). Some examples of risks to individuals are shown in Table 4.1 below.

Table 4.1 Individual risks of death per year in the UK

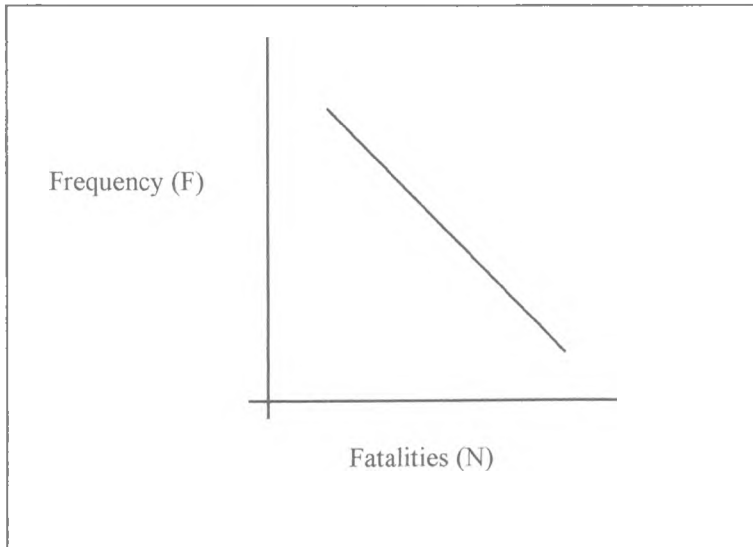
Cause of Death	Individual Risk per year
Lightning strike	0.1×10^{-6}
Air & space transport	1.2×10^{-6}
Accidental poisoning	13.1×10^{-6}
Motor vehicle accidents	101.0×10^{-6}

(after Fernandes-Russell, 1987)

The most common way in which risks are communicated is the frequency of deaths per number of population per year. However, some people consider that there are 'fates worse than death' and often the public's fear of a particular risk can bear little relation to the actual death rates (Royal Society, 1992). A well-versed example of this is the fear that many people have of flying in passenger aircraft, which (statistically) presents a much smaller risk of death than more widely accepted activities such as smoking and road transport. Risk perception is therefore not just about the biological state of the 'victim' but also considers ethical and moral issues

Societal risks are defined as frequencies with which a whole population, or a specified section of a population experience a certain level of harm from the realisation of specified hazards. The effects of the consequences of societal risks may vary over several orders of magnitude, depending on both the nature of the hazard and that of the recipient population. Fryer & Davies (1995) identify frequency – consequence (F-N) curves as the most common method of representing data on societal risks, where F (plotted on the ordinal axis) is the frequency of occurrence and N (abscissa) is the number of deaths. An example of a schematic F-N curve is shown in Figure 4.3 below.

Figure 4.3 Schematic Frequency - Consequence (F-N) Curve



Previously, undesirable drinking water quality resulting from the pollution of supplies was identified as a risk that consumers take involuntarily as drinking water is required for survival and UK tap water is assumed to be clean. Due to the nature of the water supply system, especially in Yorkshire where the inter-connected 'Yorkshire Grid' allows intra-regional transfers of water, any one source of supply may provide water to a large number of households. The risk to the quality of these supplies are therefore societal as well as involuntary

Risks have many more dimensions beyond the voluntary / involuntary and societal / individual characteristics discussed above. These primarily result from way in which risks are perceived. Risk perception varies greatly between individuals, but is a fundamentally important consideration when conducting assessments (Macgill & Berkhout, 1986). Such dimensions include whether or not the risk is known (to receptors or the scientific community in general), foreseeable, controllable, observable or socially acceptable.

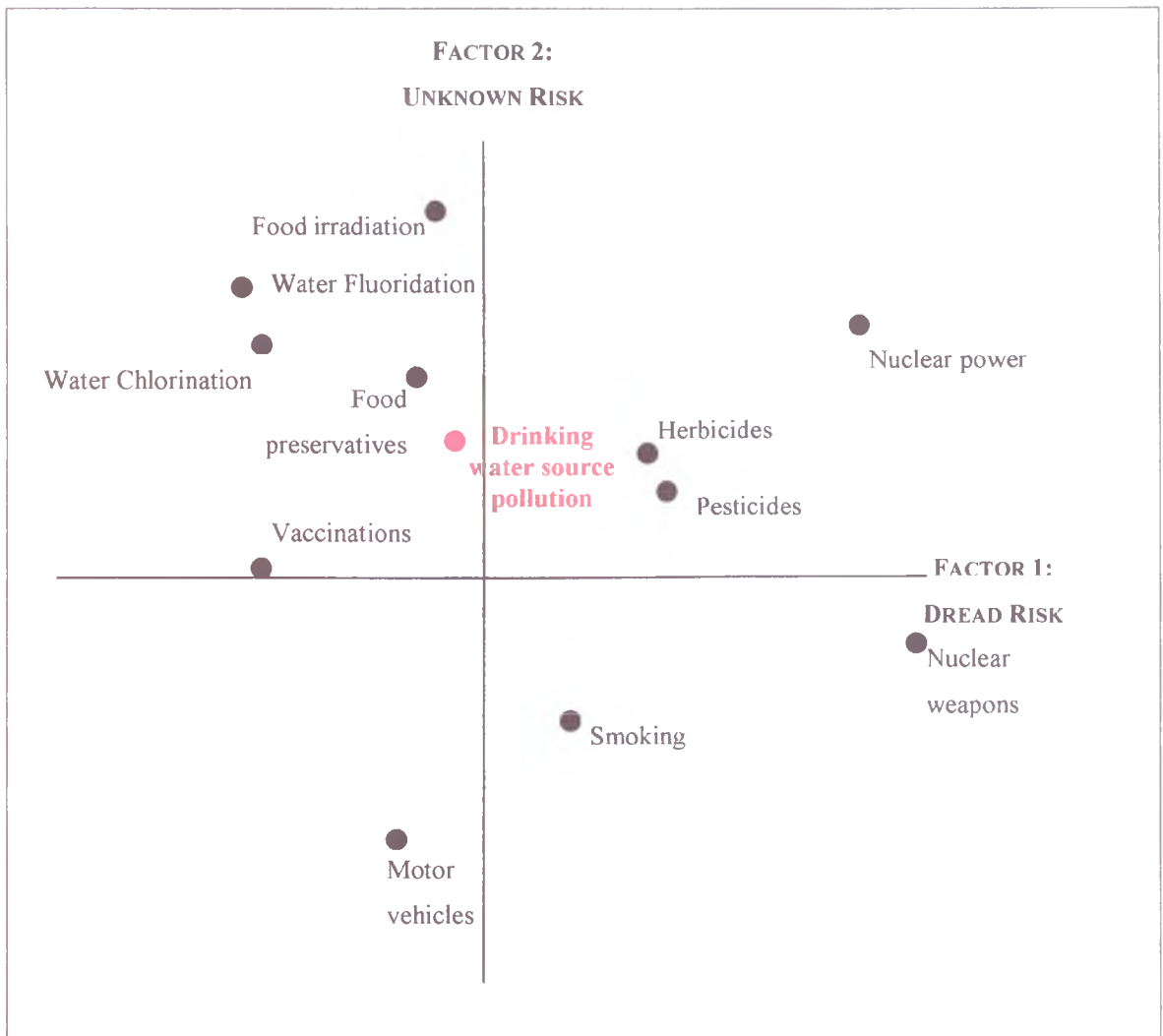
The majority of research into the formal description of risk perception has been carried out using psychometric techniques by workers such as Slovic *et al.* (1980) and Slovic (1987). The impact of these different risk dimensions on risk perception are often represented by plotting their location in *factor space*. This factor space is described by two or three co-ordinate axis each representing the characteristic of a risk. In two-dimensional factor space these characteristics are most commonly dread and familiarity (whether or not a risk is known), with the third axis often representing the number of people exposed (Royal Society, 1992). For example, the following diagram (Figure 4.4) shows the location of several different risks in factor space described by dread and the degree to which the risk is known or unknown to the those exposed.

Nuclear power and nuclear weapons appear on the far right of the diagram as the risk they represented to the respondents in the surveys was perceived as being one of particular dread. However, the respondents felt that the risks posed by nuclear power were much less well known or understood than the impacts of nuclear weapons. In contrast, the risk from motor vehicles is better known and less feared, hence the position in the lower left quadrant of the diagram. This positioning may also be the result of more respondents having direct experience of motor vehicles and their associated risks.

Drinking water quality in general has not previously been represented in factor space such as that seen above. Drinking water fluoridation and chlorination have been described in dread / unknown factor space, but these refer only to the public perception of the effects of treatment processes and not risks to the overall quality of drinking water posed by source pollution. Figure 4.4 shows the location of drinking water fluoridation and chlorination. The predicted location of risks to the overall quality of drinking water posed by source pollution is also shown.

Drinking water source pollution has been placed in the upper left sector of the factor space represented in Figure 4.4. Its location describes the fact that drinking water pollution is considered to be feared more than the risks from items such as food preservatives as drinking water is necessary for survival, whereas certain food products can be avoided if desired.

Figure 4.4 Drinking water source pollution in dread – known factor space



Partially based on the findings of Slovic *et al.* (1980) & Slovic (1987)

Contaminated water is not usually dreaded as much as catastrophic events such as nuclear warfare. However, despite the fact that risks posed by individual substances may be known to the scientific community as a result of toxicology testing, the effects of numerous substances in contaminated supplies is poorly understood and the majority of drinking water consumers, i.e. the receptor population, will know little as to the health impacts of water pollution incidents or their effects on regulatory compliance for the supply company. However, knowledge of toxicity and epidemiology is improving, as is the historical database of incidents from which conclusions can be drawn. Drinking water source pollution is not considered to be as great an unknown risk as chlorination and fluoridation were at the time of the 1980 study by Slovic *et al.*, due to this increasing knowledge and the 'safety buffer' of the treatment stage following the abstraction of supplies.

Pesticides and herbicides are major potential polluters of drinking water supplies, especially in upland catchment areas, but drinking water pollution risks in general are not considered to be dreaded as much for two reasons. Firstly, other pathways exist by which pesticides and herbicides can affect receptors besides contaminated water, and secondly numerous other water quality parameters more commonly experienced by consumers (e.g. discoloured water) have lower potential toxicological effects, hence reducing the dread factor. The position of drinking water source pollution will vary depending on the perception of those questioned and as scientists, water company employees and their customers become more aware of the potential impact of polluted supply catchments. The location theorised above is therefore not intended to represent the 'correct position' but to present a starting point from which further research or discussion can progress.

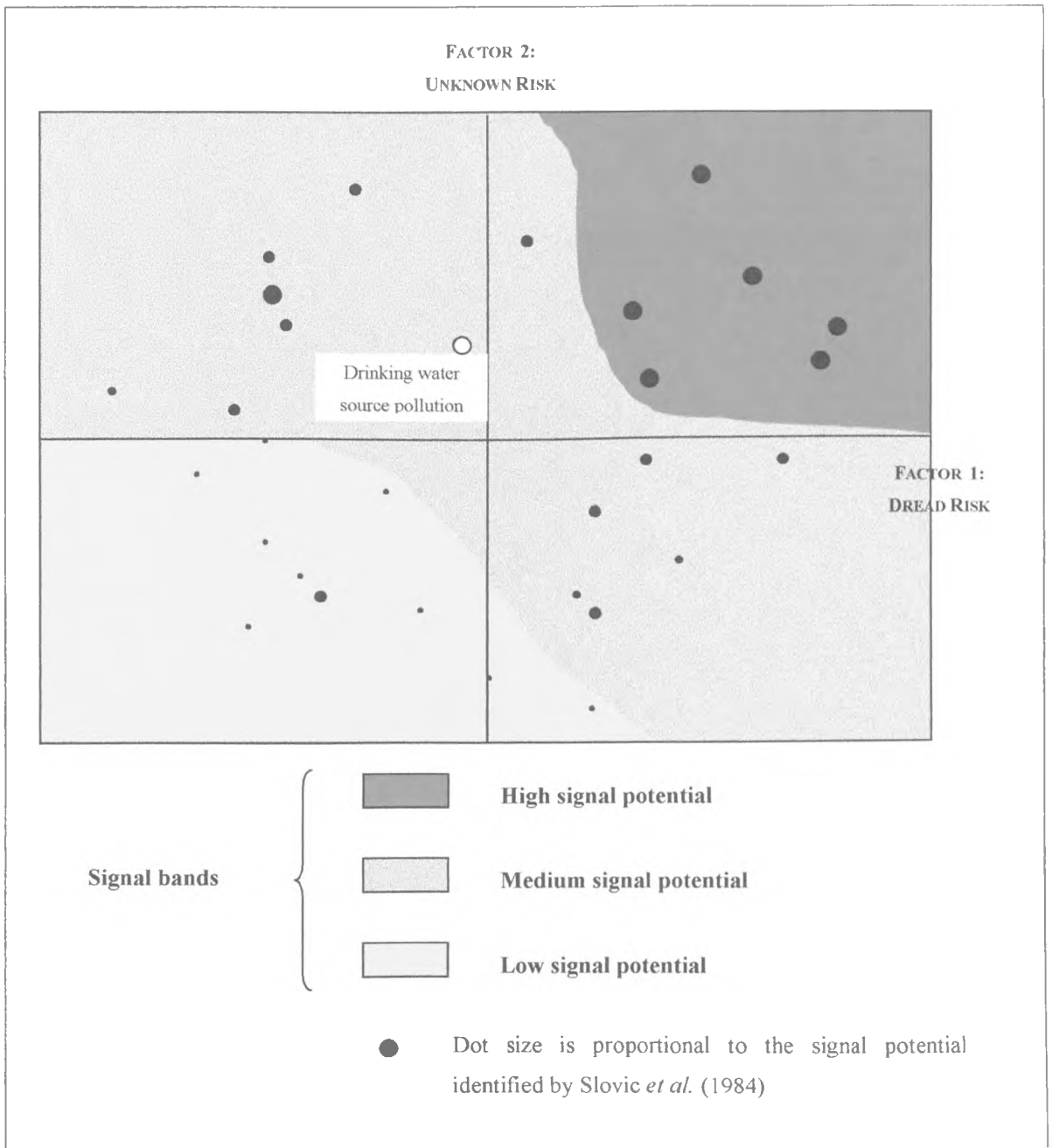
The social propagation and amplification of risk perceptions can also greatly affect the way in which many people view the components of a risk. Slovic (1993) likens this propagation to the effect of ripples in a pond, in that risks may have much wider ranging impacts than first observed. These may be impacts to the environment, a single industrial sector or across social, administrative or sector boundaries. Slovic (1993) uses the accident at Three Mile Island to illustrate this concept in that although no deaths occurred at the time of the accident and very few latent cancer victims are expected, the accident had a huge social impact on the perception of risks from nuclear radiation. The impacts of the accident not only affected the nuclear industry itself but also influenced international policies and practices involving the use of nuclear power. These are known as *signal values*. The signal value describes the extent to which the perception of the risks will inform society about future risks (Slovic, 1993).

Slovic *et al.* (1984) attempted to predict how these signal values are related to the risk characterisations represented in dread - unknown factor space. The signal potential (signal value) was found to be systematically related to risk characterisation, in that events occurring as part of a well understood system have less effect than the occurrence of an event that is little understood (Slovic, 1993). This increased impact will result from the improved awareness of receptors of the existence of a potential risk. A variation of this approach is presented below where the findings of Slovic *et al.* (1984) and Slovic (1993) are converted to isolines representing differing bands of signal potential. The location of drinking water quality theorised above is also shown on the diagram (Figure 4.5).

The predicted location of risks from drinking water source pollution in factor space places it in the 'Medium signal potential' band in Figure 4.5. This is in agreement with the anticipated effects of a drinking water pollution incident which will mainly impact the supply companies and their customers, but are likely to extend to other industrial sectors (especially if these sectors caused the pollution incident). Recent media attention will also increase the public awareness of drinking water quality issues, although such an incident is unlikely to have a major impact on governmental and international attitudes and policies that may arise from the effects of nuclear radiation.

Human perception, risk propagation and the extended social impacts of risks are areas often neglected in probabilistic risk assessments. Efforts will be made to consider these in the methodology, although, assessing the 'ripple' effects of media impacts on public perceptions of the water industry is particularly challenging given the adverse publicity of recent droughts, after which water companies have been considered 'fair game' by the media.

Figure 4.5 Drinking water source pollution signal potential



These sociological dimensions of risk and their impacts on risk assessment and perception have received little attention from the engineering and scientific community managing the water environment and offer the potential for extensive further investigation, but only once a coherent methodology for assessing such risks has been developed and tested. Also, such discussions appear to be of limited interest to the economic decision makers and managers of the intake plant and distribution network, if no methodology for assessing the risks is in place. The sociological contexts of risks to drinking water quality are therefore not investigated extensively in this research, but reference will be made to their impacts throughout the assessment procedure, especially when considering the communication of the assessment findings.

4.2.3 Summary – defining a risk to the quality of drinking water supplies

Consideration of the various definitions and approaches used in the risk literature discussed above has indicated the need to carefully define the terms *hazard* and *risk*. These terms were explicitly defined in Figure 4.2.

It is a condition of the water undertakers' Operating Licences that they must supply water to the quality standards specified by the Water Supply (Water Quality) Regulations (Section 2.2). Due to the 'catch-all' nature of these drinking water regulations it is an offence to supply water containing any substance that may impact on public health and supply companies can be fined through the courts. The definitions of risk and hazard therefore not only cover the public health impacts, but also the legal and economic implications of supplying poor quality water.

As well as defining the terms risk and hazard for use in this research, the above section has identified pollution risks to water supplies as being involuntary and societal in nature. This categorisation is an important stage in the risk assessment and should be taken into account throughout the processes of assessment and management. The position of drinking water source pollution in factor space has been hypothesised and the signal potential of such risks discussed. The inferences into the location of drinking water quality risk in factor space and its propagation potential presented above can be used to place drinking water quality risks in a wider context when communicating them to the public and will have an input into the methodology defined in this work.

4.3 Risk assessment

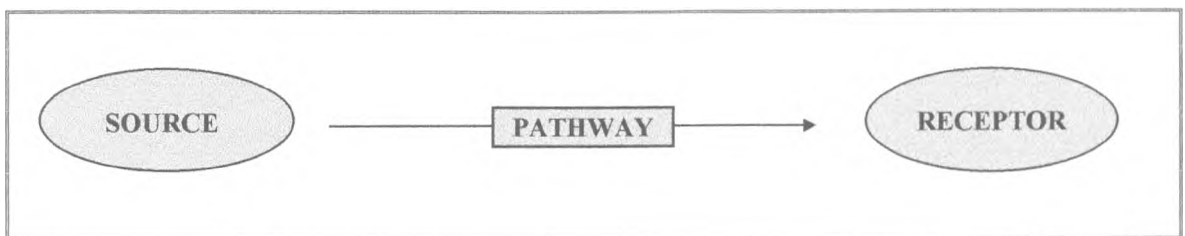
4.3.1 Introduction

Risk assessment is a structured, often complex process that can be varied to suit the particular requirements of an individual application. Risk assessments of varying levels of complexity can be used to study different types of risk some of which were discussed in the previous section. This section outlines several of the procedures most relevant to the assessment of environmental risks, and those relating specifically to the quality of drinking water. Further discussions of four particularly relevant studies can be found in the first section of Chapter 5. The views of several workers on the precise definition of the term risk assessment are put forward and summarised. The common stages involved in the process of risk assessment are then described in detail

4.3.2 Risk assessments – what are they and how are they carried out?

Essentially all risk assessments are based around the source - pathway - receptor model seen in Figure 4.6.

Figure 4.6 The fundamental basis of a risk assessment: the source - pathway - receptor model



Initially, the source of a risk must be identified and its properties assessed. The pathway is then traced to determine the impact or consequence on the receptor. Pathways can vary both spatially and temporally and involve several facets of the global environment. Receptors can be a living being, a population of beings, or the environment as a whole.

The previous section identified a risk as the combination of the frequency and consequence of a particular hazard. Risk assessment involves the identification, estimation and interpretation of these risks. Essentially a risk assessment is the determination of how often a situation is likely to arise and what the possible results are. The methodology used to carry out the assessment varies in content and is often adapted to a particular purpose. In general however, a risk assessment can be considered as a multi-stage process consisting of a frequency estimation and a consequence analysis (Cutter, 1993; Gerrard, 1995), thus addressing the two properties of a risk (identified in Section 4.2.1).

This two-dimensionality is acknowledged in the formal definition of a risk assessment given by the UK Department of the Environment which considers both risk estimation and risk evaluation as fundamental to the process of risk assessment (Department of the Environment, 1995). The Royal Society define a risk assessment in a similar way:

“the integrated analysis of the risks inherent in a product, system or plant and their significance in an appropriate context”

(Royal Society, 1992. p.4)

The two-stage approach defined above (which mirrors the two-dimensional definition of a risk) is often sub-divided into several stages. The actions taken in each of these stages is dependent on the field of application and numerous interpretations will be discussed in later sections. Jones (1992) defines a risk assessment in terms of the rigorous quantification of the likelihood of events occurring, the likelihood of harm being caused and some judgement on the significance of the results gained. This is similar to the view of Hertz & Thomas (1983) who summarise the whole process of risk assessment as three stages: identification, estimation and evaluation. The US National Academy of Sciences (1982) cite a four-stage approach, criticised by Wilson & Clark (1991) for considering risk evaluation and management as separate processes. The assessment procedure described involves hazard identification, dose-response assessment (what is the relationship between dose and incidence in humans?), exposure assessment (what doses are experienced under different conditions?) and risk characterisation (what is the incidence of adverse effects?) (National Academy of Sciences, 1982).

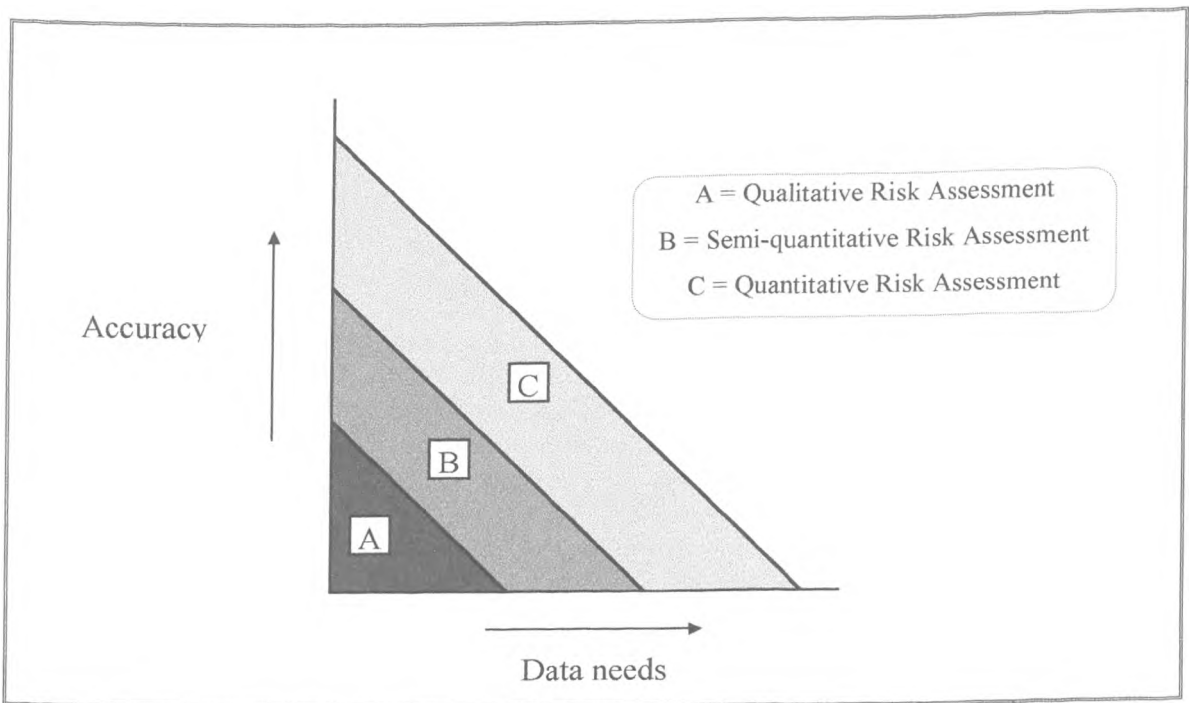
4.3.3 Types of risk assessments

Risk assessments vary from deterministic to probabilistic in nature (Fryer & Davies, 1995). A deterministic risk assessment is based on the use of one initial parameter for each section of a system under consideration, for example a single value for river discharge, as opposed to a range of possible values. Deterministic assessments are often used to provide information on ‘worst case scenarios’. In contrast a probabilistic assessment considers a range of possible initiating parameters and outcomes. Following the above example, a probabilistic assessment would consider a variety of river flows. Both deterministic and probabilistic techniques have been used to assess pollution risks to both surface waters (Keller & Wilson, 1992; Eddowes, 1995) and groundwater (Morrey *et al.*, 1995; Pollard *et al.*, 1995).

Within these types of assessment, a variety of approaches can be taken. These are usually qualitative, semi-quantitative or quantitative. A quantitative risk assessment is often considered most desirable as it allows the risks involved to be quantified numerically as opposed to a subjective high risk - low risk approach, thus aiding the communication of results to third parties (who may not be risk specialists). These assessments are usually probabilistic, due to their numerical bias.

However as Figure 4.7 shows, probabilistic quantitative assessments require considerably more data input than qualitative ones. The choice of which approach to use should be based not only on the data requirements and resources available, but also the intended audience of the assessment. This is true of all stages of the assessment process from hazard identification to risk estimation and management, and is mainly because quantitative assessments are derived from probabilistic studies which concentrate on the determination of numerical values to represent risks. A qualitative approach is therefore more desirable where data sources are limited or unsuitable for use in probabilistic estimates and the output is equally valid as that from a quantitative one.

Figure 4.7 Types of probabilistic risk assessment and their data requirements



A risk assessment does not have to be described exclusively into one of these three categories as many assessments will involve both quantitative and qualitative aspects as the process progresses and a flexible approach is often the most appropriate course of action. This research will therefore use quantitative, qualitative and semi-qualitative approaches.

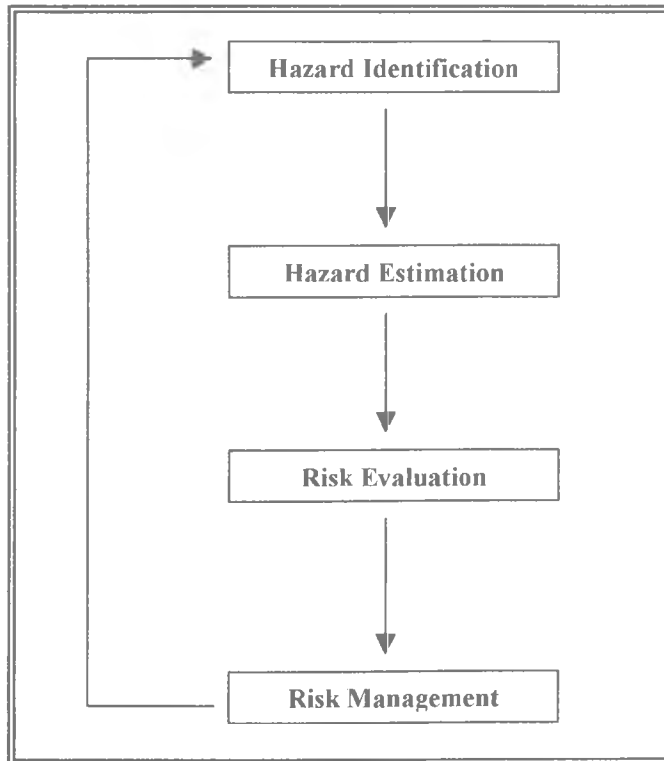
4.3.4 Previous approaches to environmental risk assessment

Study of the risk literature shows numerous variations in the framework or structure of risk assessment processes which reflects the wide use of risk assessments across a variety of fields including the financial, industrial and environmental sectors of society. As stated in the previous section, when investigating pollution risks in water supply catchments it is more prudent to consider the approaches used in the environmental field.

Kates (1978) refers specifically to environmental hazards and defines an environmental risk assessment as an appraisal of both the type and magnitude of the threat posed by an environmental hazard, which again considers both the occurrence of a hazard and its consequences. Kates (1978) considers there to be three elements involved in the appraisal of these hazards, hazard identification, risk estimation and social evaluation, all of which overlap to form the assessment process. He suggests that the process of risk assessment can be summarised by three key questions: 1) *What constitutes a threat? (hazard identification)*; 2) *How great are the consequences and how often do they occur? (risk estimation)* and 3) *How important is the estimated risk? (social evaluation)* (Kates, 1978).

Comparing this to some of the more generalised methodologies seen above, it is noticeable that as with the National Academy of Sciences method, the final stage of risk management is missing from the assessment. Risk management is fundamentally important to a risk assessment and is essential to ensure the whole process becomes iterative. Gerrard (1995) suggests that an environmental risk assessment should include the evaluation, mitigation and monitoring of risks once they have been identified. This therefore includes elements of risk management, mirroring the approach of Eddowes (1995).

Consideration of a selection of the approaches recommended for risk assessment in the literature (Kates, 1978; National Academy of Sciences, 1982; Hertz & Thomas, 1983; Cole *et al*, 1988; Wilson & Clark, 1991; Jones, 1992; Keller & Wilson, 1992; Royal Society, 1992; Department of the Environment, 1995; Eddowes, 1995; Fryer & Davies, 1995; Gerrard, 1995), has identified common themes running through risk assessments methodologies. These can be summarised by dividing the risk assessment process into four stages: *hazard identification*, *hazard estimation*, *risk evaluation* and *risk management*. The definition of the term risk assessment can therefore be generalised as the process of identifying, estimating, evaluating and managing a risk as shown in Figure 4.8. The four stages are discussed in more detail below.

Figure 4.8 General framework of a risk assessment procedure

Hazard Identification

Hazard identification essentially involves answering the question “*What can go wrong?*”. It should include consideration of all the possible situations that could lead to harm to humans or the environment. The identification process usually involves the logical analysis of a sequence of events that could lead to these situations arising. These events can be considered to be either external (e.g. earthquakes), or internal (e.g. human error) (Fryer & Davies, 1995). There are numerous ways to carry out hazard identification that may be applied in different situations. However, no one pre-defined technique may be sufficient to determine all the possible hazards present in a given situation.

The most common techniques are checklists, hazard indices, fault and event trees, Hazard and Operability Studies (HAZOPS) and Failure Modes and Effects Analysis (FMEA). Distinct similarities exist between these techniques and they are often used in conjunction with one another. Other methods such as Monte Carlo simulation and Time-Petri nets can also be used but are much less common in environmental applications (Kletz, 1992; Fryer & Davies, 1995) and are therefore not considered in detail here.

Checklists involve the identification of a risk through the completion of a series of questions about a process or activity. These questions are often the result of past experience or knowledge. Carrying out a checklist-type operation relies heavily on the expertise of both the person formulating the questions in the first place and that of the person answering the questions. This approach to hazard identification is best applied to situations in which the assessors are familiar, as it may otherwise result in a number hazards remaining unidentified as previously unknown hazards will be omitted. Carrying out a checklist-based exercise is therefore more re-active than pro-active and has greatest potential for use as the first step of the hazard identification process.

Hazard indices are designed to quantify the relative potential of occurrence of hazardous incidents associated with a given activity or process. They are inventories of materials related to their potential to cause harm. Several types of indices are seen in the engineering and risk literature, examples of which are the maximum permissible concentration of a substance in water or air, lethal doses or concentrations (LD / LC) (Keller & Wilson, 1992; Royal Society, 1992) and Suggested No Adverse Response Levels (SNARLS) (Eddowes, 1995; Fryer & Davies, 1995). Hazard indices may be based on criteria such as the heat of combustion or limits of toxicity. A well known example of this approach is the Dow Index for fire and explosions (Dow Chemical Company, 1987). A common criticism of hazard indices is their inability to account for human error in a plant or process and this should be borne in mind where these indices are used. Several workers have made use of hazard indices to assess the risks to drinking water quality and human health (see for example, Lamb & Keller, 1987; Keller & Wilson, 1989; Eddowes, 1995).

The systematic nature of many hazard identification approaches results in some formalised structure, such as a flow diagram being used. This may be clearly defined and followed, or it may be an unconscious action by the risk assessor when carrying out the hazard identification (Fryer & Davies, 1995). Logic trees are a common way of representing a logical process or relationship. The logical manner of many hazard identification techniques enables logic tree structures to be used to facilitate this process. Logic trees are useful for both identifying hazards and assessing hazard probability and consequence and therefore are also discussed in later sections. Gardner (1992) describes logic trees as:

“two-dimensional geometric figures with spatial relations that are representative of a logical argument.”

(Gardner, 1992, p.9).

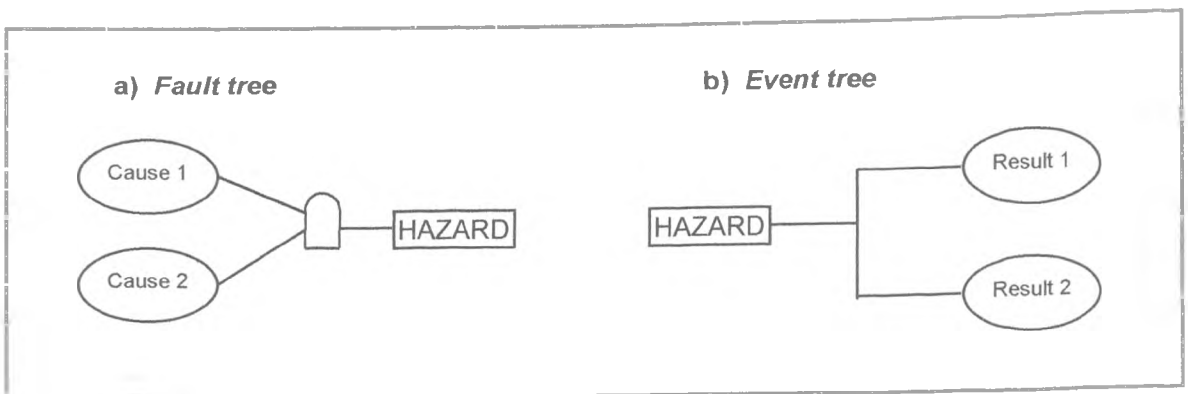
Logic trees enable complex processes to be more easily visualised and understood by dividing them into simpler constituent parts. However, the relationships between these sub-parts are maintained in the tree structure, thus allowing common-cause events to be considered. Logic diagrams are often used in the assessment of environmental risks as they allow the complex amalgam of processes operating in the natural environment to be represented more clearly.

Several types of logic structures are utilised in risk assessments, the two most common being Event Trees and Fault Trees (see for example, Parr & Cullen, 1988; Crossland *et al.*, 1992). Actually carrying out the logical analysis of all the possible causes of a hazard is a significant part of the risk assessment process as it widens the focus of the assessor's minds, encouraging them to think logically through all the systems and processes being assessed.

Event Trees specify a range of possible outcomes from an initiating event (a 'bottom-up' approach). Therefore the frequency of an outcome can be calculated arithmetically from the frequency of the initial event and the probability of each of the intervening steps. These are often referred to as 'accident chains' in the engineering literature. An example application of an event tree is the estimation of the socio-economic impacts and costs of 'seeding' hurricanes (Howard *et al.*, 1973). A simple event tree can be seen in Figure 4.9 b).

Fault Trees are designed to perform the opposite of event trees in that they work back from an event (the 'root' or 'top' event) through all the possible precursors of this outcome (i.e. its causes). These causes are then broken down into events that caused them and so on. Eventually the base events (or 'leaves') will be established, the combination of which is responsible for the existence (and realisation) of a hazard. The causes responsible for an individual event can be combined using logic AND gates (where both causes must combine to produce a hazard) or by using logic OR gates (where either causes can result in the hazard). Common examples of the use of fault trees are quantifying the risk from the failure of engineering structures / machinery such as valves and pipelines. A simple fault tree can be seen in Figure 4.9 a).

Figure 4.9 Example Fault and Event trees



For both types of tree to be logically sound the contents of one tier or layer must fully explain the next layer in the sequence. This can be a useful aid in ensuring a thorough hazard identification procedure has been adopted.

Fault trees are therefore extremely useful for hazard identification as they follow a logical course from the realisation of a known risk, back through all the possible hazards that may have caused it. Care must be taken when applying these trees as only the hazards that cause known risks will be identified. It is

therefore necessary (for the purposes of hazard identification) to ensure that the 'leaves' of a fault tree are representative of all the possible causes of a particular hazard that may exist in a given system. It is also important to obtain comprehensive information about all the possible types of hazard that may exist in an area so that all pre-cursor events can be thoroughly investigated.

Hazard and Operability (HAZOP) studies are a hazard identification technique widely used in the chemical, petrochemical and nuclear industries, but are applicable to a wide range of activities. A HAZOP study is carried out by a multi-disciplinary team and is also done in a systematic way, for example by following a flow chart representing a manufacturing process. The use of logic trees, such as those introduced above, to describe all or part of the process is common. The HAZOP technique avoids omitting previously unknown risks (a problem of the checklist approach) by using open-ended querying using key phrases such as "part of", "more than" and "less than" (Kletz, 1992). The methodology combines the knowledge and experience of the experts in the team, and techniques such as fault and event tree analysis (using the open-ended query approach) to identify the causes and consequences of hazards in a particular situation. Typically, a HAZOP team in a chemical plant would involve design engineers, process engineers, instrumentation engineers and an independent chairman who specialises in HAZOP techniques. A HAZOP study can be used for the whole risk assessment process in that it identifies deviations from the 'normal' practice, their causes and consequences. It does not however consider the probability of an event occurring and the success of the study relies heavily on the experience of the HAZOP team (Fryer & Davies, 1995). HAZOP studies are now commonly used to assess the potential risk at water treatment and sewage treatment works throughout the UK. A comprehensive description of the complex HAZOP technique can be found in Kletz (1992).

Failure Modes and Effects Analysis (FMEA) is similar to the HAZOPS approach in that it identifies the cause of a hazard from a knowledge of the equipment or process under scrutiny and its modes of failure (Lees, 1980). Once the nature of the possible failures and hazards have been identified, the effects on the rest of the system or process can be investigated. An FMEA study involves breaking down a process or system into sub-units, then identifying the possible failure modes, estimating their probability and categorising their effects. Event trees are often used for this purpose. Effects are usually categorised into death or personal injury, damage to equipment or capital investments and economic loss resulting from the failure (Fryer & Davies, 1995), thus going beyond pure hazard identification into considerations of frequency and consequence. The probabilities and effects can be combined in a criticality matrix, which can help identify the crucial sub-units of the system or process and therefore prioritise risk mitigation actions.

There are several criticisms of the methods of hazard identification discussed above. Firstly, many of the approaches split a system or process into sub-units and may therefore omit common-cause elements in the identification process. Secondly, the methods have little provision for the incorporation of human error and thirdly, all of the above methods rely on the expertise of the assessors involved. There is therefore no

one method that guarantees complete hazard identification and several recognised techniques may need to be combined or a novel approach considered in order to attain the optimal hazard identification.

Previous studies of pollution risk assessment have made only sporadic use of the formalised techniques for hazard identification described above, although Cullen (1996) highlights the importance of a number of these techniques, especially checklists, in risk applications in the UK water industry. Fault and event trees are used by Parr & Cullen (1988) to assess the risk of flooding from a large reservoir. Groundwater risk assessments carried out by WRc involve the use of systematic flow charts, similar to the logic tree method (WRc, 1996). Cole *et al* (1988) and Morrey *et al* (1995) did not report the use of formalised techniques in their risk assessment procedures although, as discussed previously they may be carried out sub-consciously by the assessors. Whether the formalisation of the hazard identification process is always carried out consciously is a focus of some debate, however, the obvious benefits of doing this include the potential for generic applications and constant re-assessment. Formal hazard identification techniques are therefore fundamental to the development of a transparent, generic methodology.

Of the approaches to hazard identification discussed above, the use of fault and event trees, with both quantitative and qualitative descriptors presents the most flexible method for comprehensively identifying hazards. Facets of the other approaches can also be incorporated to ensure that all possible hazards are identified. In the case of pollution from supply catchment areas, fault and event trees have a great deal of potential as they can be used to identify a variety of water quality hazards. Point sources of pollution can be identified using commonly applied techniques to industrial or other potentially contaminating sites. Non-point source hazards can be identified by using a logic tree approach as catchment characteristics and hydrological regimes known to cause such problems can be combined using the tree structures to identify areas of potential hazard. The use of logic trees also enables a consistent approach to be carried forward into the hazard estimation stage of an assessment as discussed above. The further development of these approaches is described in more detail in following chapters.

Hazard Estimation

Once the existence and nature of a hazard have been identified the next stage of a risk assessment is to prepare an estimate of hazard probability. This involves considering how likely it is that the set of circumstances responsible for producing a hazard will occur. For example, estimating the frequency of travel of toxic chemicals along a certain route coinciding with certain weather conditions and traffic levels. Risk estimation involves the determination of a probability per unit time of each of the hazards (identified using hazard identification techniques) occurring. This process is also referred to as *frequency analysis* (Cutter, 1993; Fryer & Davies, 1995; Gerrard, 1995) and involves combining an assessment of the statistical probability of each of the contributing variables. The probability is then expressed as a frequency, with one year being the normal time period considered. For example, the hazard potential of being struck by lightning is approximately one chance in ten million per year (Table 4.1).

As with the risk assessment process as a whole, risk estimation can be considered as qualitative, semi-quantitative or quantitative. The expression of a probability may therefore vary from a 'precise' number of occurrences per year (or other suitable time period), to a qualitative assessment of high, medium or low frequency. Any estimate of hazard frequency will be semi-quantitative or qualitative unless the occurrence of a particular hazard is well documented under exactly the same conditions as those being assessed. Hence the term risk *estimation*. There are two common sources of these estimates. The study of historical data can enable frequencies to be estimated from past experiences, or fault and event trees can be used to synthesise a frequency estimate.

As noted previously, fault and event tree analysis can be used in hazard identification, but they are more commonly used in hazard estimation. If probabilities can be assigned to the base events (or leaves) of a fault tree then a frequency of the top event can be calculated algebraically. Probability values for the base events may be gleaned from manufacturers' failure records, historical data records or from expert judgement (Dickson, 1991; Fryer & Davies, 1995). The aim of hazard estimation using fault trees is to stop the analysis once a point is reached at which probability values are known or can be estimated for all the causal events.

Estimating hazard frequencies from historical data involves the study of hazard occurrence throughout past records and the extrapolation of these trends into the future. This method can only be applied where sufficient historical data are available and these data are directly relevant to the system or process under study. However, estimating the frequency of an 'end result' does not necessarily consider variations in individual precursors that may subsequently affect the frequency of a resulting hazard. Another problem of this method is that sufficient data are very rarely available to allow sound extrapolations.

Obtaining the necessary data to assign accurately the probabilities associated with risk estimation can be very problematic. Much of the data required in such circumstances may be commercially sensitive, especially data regarding system reliability and safety records. There are however numerous sources of data available in the published literature as well as various commercial and company databases (Lees, 1980; Fryer & Davies, 1995). Experimental testing can also give an indication of the reliability of components, some examples of which are shown in Table 4.2.

Table 4.2 Example equipment failure rates.

Item	Failure Rate (failures / 10 ⁶ h)
Electric motors	10.0
Pipe joints	0.5
Control valves	30.0
Pressure valves	3.0

(after Lees, 1980)

Values other than probabilities can be attributed to the tree branches (or branching nodes) but the units must be consistent throughout the tree. Fault trees are primarily used in engineering studies to prepare quantitative risk assessments (e.g. Crossland *et al*, 1992; Department of the Environment, 1995) but can be equally useful in preparing qualitative assessments by using qualitative labels on the branches such as 'high', 'medium' or 'low' probability of occurrence.

Fault trees can also be used to establish the minimum number of events needed to cause a hazard (Dickson, 1991). Estimating the minimum number of events needed to cause the top event can be done easily on simple fault trees, however where complex trees are developed with several layers this becomes more difficult. The minimum number of events can be determined mathematically, but this is only appropriate where the tree branches are attributed numerical values. An alternative method is the use of matrices (Dickson, 1991). The calculation of the minimum number of events using matrices begins by listing all the gates in the fault tree, their type (AND / OR) and the number and name of their inputs. A series of matrix charts are then drawn up in which individual gates can be substituted by their inputs. This is continued until all the gates are represented by base events, at which point the minimum number of these required to cause a hazard (and which events they are) can be identified from the matrix. Such information is potentially useful when determining and prioritising risk mitigation measures.

Event trees, as described previously, employ a 'bottom-up' approach. The tree progresses by a series of binary branches which connect together individual nodes. The nodes represent a component or system and the frequency of an occurrence can be calculated by combining the frequencies of nodes mathematically. Again frequencies can be derived from historical data or they may be the result of a fault tree analysis of the system or process represented by the node. Unlike a fault tree, a complex event tree can potentially display the existence and frequency of a number of outcomes (Lees, 1980). In water quality studies event trees can therefore be used to estimate multiple possible outcomes of a pollution event.

Estimates of probability will vary depending on the impact being considered. The method of transfer to the recipient is often described as the 'pathway' section of the source-pathway-receptor model described earlier i.e. precisely how a receptor comes into contact with a hazard. Information on the hazard pathways should be evident from the earlier assessments, particularly if fault and event trees are used. The nature of the pathway(s) by which a hazard takes effect will have a significant impact on the probability of occurrence. For example a gaseous chemical release into the atmosphere may affect a much wider spatial area and be transported at different rates than a liquid spill to an impermeable, bunded area. Stonehouse & Mumford, (1994) recommend the use of mathematical models to describe the hazard pathways. The PRAIRIE approach to pollution risk assessment utilises a mathematical model to describe the pathway section of the assessment. Here a combination of Manning's formula and the DYNUT aquatic dispersion model represents the spatial and temporal dispersion of a pollution incident downstream (Welsh, 1992). Similar models have also been developed to assess the risks of pollutant dispersion in marine waters (Ganoulis, 1991) and the atmosphere (Chambers *et al*, 1991)

The use of logic tree structures can also help in the simplification of pathway estimates by subdividing the pathway into known constituent parts. Once a receptor comes into contact with the hazard then the impact on the receptor is governed by both the toxicity of the hazard (for chemical and public health hazards) and its acceptability. These are considered in the following section, although these differing impacts may necessitate individual assessments of probability.

Whilst being identified by many workers as established tools for risk assessment (e.g. Kates, 1978; Dickson, 1991; Royal Society, 1992; Department of the Environment, 1995; Eddowes, 1995; Fryer & Davies, 1995; Cullen, 1996), fault and event trees have not previously been used to assess risks to surface water intakes. The use of logic tree structures will therefore form a novel, but important facet of the risk assessment methodology described in this research.

Risk Evaluation

Risk evaluation is the process of determining the significance or value of the identified hazards and estimated risks, to those concerned with or affected by them (Royal Society, 1992). Once the nature and frequency of a hazard have been determined, some indication of its consequences is necessary in order to assess the risk (Section 4.2.1). Risk evaluation (also called consequence analysis / modelling) utilises the output from both the hazard identification and hazard estimation activities.

The evaluation of the estimated risk is a key element of the risk assessment as it involves a judgement about how significant the identified hazards are. As with other stages of an assessment, the results of this evaluation may be expressed either qualitatively or quantitatively, depending on the expertise of the assessors, the methodologies used and the intended audience (Macgill & Snowball, 1982). Rimmington (1995) considers it to be at this stage where the broadly scientific process of risk assessment interacts with the social, economic and politic inclinations of the decision makers.

In economic theory, evaluation judgements are made with respect to the monetary value of the damage (potentially) caused by the hazard. In terms of environmental risks such valuations are plagued with difficulties and environmental risks are more often quantified in terms of their potential effect on the future sustainability of the environment (Department of the Environment, 1995). The study of pollution hazards to drinking water adds the further dimension of human health and toxicity judgements must therefore be considered.

There are a number of effects that undesirable water quality may have on human receptors. These range from unpleasant tastes and odours, through gastrointestinal infections to severe effects requiring medical attention and possibly death. However, the data required to formulate dose-response relationships for drinking water and hence estimate risk are either poorly understood or very sparse (Stanwell-Smith, 1993; Fryer & Nixon, 1995). Data on the human toxicity of chemicals in general are sparse and most available information refers to a substance's toxicity to animals. These are normally expressed in terms of the LD₅₀ (the Lethal Dose in mg/kg bodyweight for 50% of the test population), which for use in water quality

studies can be extrapolated to Lethal Concentrations (LC_{50}). LC_5 values (the lethal concentration for 5% of the test population) have also been used in water quality studies to represent the 'dangerous dose' specified by the Health & Safety Executive (Health & Safety Executive, 1989) as a dose with the potential to cause death (Fryer & Nixon, 1995). Fryer & Nixon (1995) recommend an extrapolation factor of one hundred to convert an animal LC to a human LC. Other common methods of expressing toxicity to humans are 7-day and 24-hour SNARLs (Suggested No Adverse Response Levels) and NOELs (No Observable Effect Levels) both of which can be used to indicate potential levels of concern for a substance (Suckling *et al*, 1992, Fryer & Davies, 1995).

The Environment Agency's approach to hazard evaluation is based on the comparison of the lethal concentrations mentioned earlier. The significance of a hazard is measured in terms of the LC_{50} , the LC_5 and the 7-day and 24-hour SNARLs (Eddowes, 1995; Fryer & Nixon, 1995). Lethal concentrations are also used by Lamb & Keller (1987) in their PARI methodology to determine hazard acceptability, but as with the risk assessment methodology described by Fryer & Nixon (1995), this procedure is intended for application to existing or proposed industrial sites where the concentrations of chemicals stored are known. Potential maximum concentrations can therefore be calculated and compared to the acceptable concentrations and hazard frequencies specified by organisations such as the Health & Safety Executive.

Section 2.2 stated that the use of the chemical and biological standards specified in the drinking water regulations address both toxicity and the financial and legal implications of a pollution incident in a supply catchment. These regulations are therefore used as the benchmark for both hazard estimation and risk evaluation. The probability of a compliance failure of these regulations can be used to estimate risk occurrence and magnitude. (Estimates of magnitude can be based on the extent to which the standards are exceeded and toxicity levels). The use of treated water standards such as these not only introduces a safety factor (Morrey *et al*, 1995; Pollard *et al*, 1995), but also allows the methodology to be easily revised to incorporate new legislation. Hazard estimation using the standards specified in the drinking water regulations is discussed further in later chapters.

Risk evaluation at a societal level needs to be carried out in combination with an understanding of risk perception. Risk perception involves the consideration of people's beliefs, attitudes, judgements and feelings as well as the underlying social and cultural values. The social acceptability of a risk will vary greatly depending on the views of the person studying the risk assessment output with individuals forming their own unique assessment of the significance of risks as a result of their personal knowledge and experiences. A number of factors are known to influence people's perception of a risk including familiarity, control, spatial and temporal proximity, the 'dread' factor and scale (Department of the Environment, 1995).

The perception of risks also influences the effectiveness of risk communication. Risk management decisions must take into account the sociological dimensions of risk perception and it is therefore not possible to simply split risks into 'acceptable' and 'unacceptable' categories but they must be considered on a rolling scale that includes factors such as familiarity and scale.

Considering the risks of water quality in particular, people are less likely to be aware of the limited statistical data regarding the health effects of drinking water quality and may therefore base their perceptions on secondary sources of knowledge. Thus 'high-profile' media issues such as microbiological and viral contamination of water and more recently speculation that Bovine Spongiform Encapalopothy (BSE - linked to the human brain disease CJD) can contaminate drinking water supplies may significantly influence the public's perception of drinking water quality (Anon., 1996).

Risk Management

Risk management can be considered as the fundamental reason for carrying out a risk assessment. Unless the risks identified can be categorised as either negligible, tolerable or requiring action, and decisions made about their future then the assessment procedure will have little tangible output. Risk management is the process of implementing decisions about tolerating or altering risks (Department of the Environment, 1995). However, the implementation of all such decisions should take into account the principles that there is no such thing as zero risk and all risk reduction activities should be considered in terms of the benefits gained. Risk management decisions are often taken by different people to those who conducted the original assessment and the possible implications of the decisions should be fully understood before any action is taken. The risk management process is therefore influenced by issues external to the original assessment remit.

Underpinning all discussions of risk management is risk acceptability. There are many ways to judge risk acceptability, in the UK the ALARP (As Low As Reasonably Practicable) principle has been advocated as the preferred method of governing whether a risk is acceptable or not (Department of the Environment, 1995; Fryer & Davies, 1995; Gerrard, 1995). This principle is based around the idea that zero risk is unachievable and therefore risks should be reduced to 'as low as reasonably practicable', but only where they are intolerable or where the cost of reducing them further is still reasonable given the benefit(s) gained. In order to do this a crude cost-benefit assessment is carried out. There are three areas to the ALARP principle, in one region the risks are deemed intolerable and must be reduced regardless of the costs activity terminated. At the other end of the scale the risks are deemed negligible and no action to reduce them is necessary. The middle section is called the ALARP region. Risks which fall within this category should be reduced if the cost of doing so is reasonable in relation to the activity concerned and the benefits gained. The ALARP principle is thus supposed to be an ever-improving risk reduction device that can embrace new technologies to assist in the reduction of risk consequences (Gerrard, 1995).

Decisions to tolerate a risk may be taken where a risk is identified as negligible or where the possible implications of activities to alter the risk are considered to outweigh the benefits of risk alteration. A management decision to tolerate an environmental risk may also be conditional on additional monitoring being implemented or re-assessment assured in order to monitor whether the risk remains tolerable. Some concentrations and frequencies considered 'acceptable' based on these approaches are shown in Table 4.3 below.

Table 4.3 Acceptable SNARLs (Suggested No Adverse Response Levels) and Lethal Concentrations for drinking water intakes based on the hazard posed by an industrial installation.

Effect at intake	Acceptable frequency (per site per year)
7-day SNARL	2.0×10^{-3}
24-hour SNARL	9.0×10^{-4}
LC ₅	1×10^{-6}
LC ₅₀	1×10^{-7}

(after Fryer & Nixon, 1995)

There are two stages to be undertaken if a risk is to be altered, implementing the change and monitoring the change. The implementation of a change should ideally be carried out in association with the assessors who formulated the original assessment. This ensures that the possible impacts of the activities causing the changes can be assessed relative to the original risks and the perceived benefits. All changes should be monitored, either by direct monitoring of the altered system element or by regular re-assessment. This ensures that the whole process of risk assessment and management becomes iterative. It is therefore important to set targets for management activities, to assess the performance of activities against these targets and to carry out regular re-assessments of the risks.

4.3.5 Uncertainty in risk assessment & management

The process of risk assessment will involve some inherent uncertainties as a result of assumptions or generalisations made and inaccuracies in the data used. These uncertainties are wide ranging and can occur throughout the assessment process. Some uncertainties are quantifiable by established techniques (such as Monte Carlo analysis) whereas others are less tractable (Royal Society, 1992). The majority of the uncertainties that are experienced in risk assessments stem from the absence of vital information and the consequent reliance on inference (Youngren & Tardiff, 1991).

A major source of potential uncertainty is the initial hazard identification stage, namely whether all significant causal sequences have been identified and described. Errors at this stage will be reduced as more risk assessments are carried out as long as a 'corporate memory' is maintained by the assessment team. Inaccuracies may also occur in the hazard estimation and risk evaluation stages. Probability data are inherently imprecise as the accuracy of statistical estimations decreases away from the mean value. It is these extremes (e.g. unlikely but severe occurrences) and the interpretation of their consequences that are of most interest to the risk assessor and uncertainties in the data often exist as a result (Stonehouse & Mumford, 1994).

Uncertainties in probability and consequence data can be treated by established methods where the data sets are complete, however it is more often the case that data are incomplete and insufficient for these purposes and uncertainties of a less quantifiable nature exist through the need exercise judgement in the

data. This can be a particular problem where fault and event tree techniques are used (as proposed in this work). As such, the use of the best available data is the only way to minimise these uncertainties. The magnitude of uncertainties involved in risk assessment may seem unusually high to those interpreting the results (e.g. errors of two or three orders of magnitude) but when the frequencies under consideration are extremely low (e.g. of the order of 10^{-8} times per year) such errors are less significant (Royal Society, 1992). A reduction in uncertainty to the absolute minimum is aspired to by many assessors, but a careful balance is required between the desire for accuracy and the available resources. Younger & Tardiff (1991) and Kletz (1992) recommend the use of cost-benefit analyses to resolve this conflict and achieve the most realistic reduction of uncertainties. In many risk assessments, the limiting factor on reducing uncertainty is the financial cost of the initial data sources and the techniques employed in their assessment.

4.4 Summary: risks - definition, assessment & management

This chapter has introduced the concepts of hazards, risks and risk assessments and highlighted some of the complexities involved in their study. The importance of the precise definition of the terms and stages involved in any assessment has been discussed and the specific terminology of this research presented. Different types of risk have been identified, ranging from those that occur rarely and influence individuals, to risks that impact on whole populations on a regular basis. The difference between willing risk takers and involuntarily victims is also discussed. Risk perception has been identified as the key to communicating the findings of a risk assessment, and the way in which drinking water pollution may be perceived in relation to other risks has been theorised.

Risks to public water supplies are identified as being involuntary and societal in nature. The supplies from a single source may affect a large community and given the difficulty in detecting many pollutants and the fact that drinking water in the United Kingdom is assumed to pose little risk to human health, consumers are often unaware of any risk that may exist from their water supplies. Risks from drinking water pollution when plotted in known – dread factor space are predicted to have medium (signal) potential for propagating the impacts of risk both spatially and temporally (within, and across populations and industrial sectors).

The source - pathway - receptor model that forms the basis of many risk assessments has been introduced and some approaches to environmental risk assessment discussed. The study of a variety of risk assessment techniques in this chapter has failed to identify an existing methodology that is suitable for application to an upland water supply catchment. It has however illustrated a general structure commonly applied in environmental risk assessments and identified a wide range of techniques that can be utilised in carrying out such an assessment.

Common themes from previous assessment methodologies have been identified and summarised as a generalised four stage risk assessment process involving:

- hazard identification,
- hazard estimation,
- risk evaluation, *and*
- risk management.

The activities involved in each of these four stages have been discussed in detail and techniques such as checklists, HAZOP studies, FMEA and fault and event trees described. The importance of logic tree structures (such as fault and event trees) has been highlighted due to their potential application to several stages of the assessment procedure. Although commonly applied to probabilistic risk assessments in process industries, these trees can potentially be adapted to suit the multitude of hazards faced in a water supply catchment. Attention has also been drawn to the importance of uncertainties in the assessment process.

The four stage risk assessment framework and the use of logic trees (which are both flexible and generic in nature) will therefore form the basis of the generic methodology for assessing pollution risks to water supply intakes. The theoretical framework of a methodology based on these conclusions is described in detail in the following chapter.

Chapter 5

Theoretical framework of the methodology

5.1 Introduction

This chapter describes the theoretical framework of the risk assessment methodology developed in this research.

The first section of the chapter discusses the approaches taken by previous workers carrying out risk assessments of pollution risks to drinking water supplies. These methodologies are compared to the four stage structure described in Chapter 4. Four of the methodologies (Cole *et al*, 1988; Baron, 1989; Keller & Wilson 1992 and Eddowes, 1995) are then investigated in more detail. The techniques used in each of these methodologies are discussed and their potential for application in this study assessed. Shortfalls are identified and the need for a new approach to pollution risk assessment in upland supply catchments, such as those in Yorkshire, is highlighted.

The second section of the chapter describes the structural framework of the RASCAL (Risk Assessment of Supply Catchments And Land) methodology developed in this research. It describes the theoretical basis of the techniques that will be used in identifying, estimating, evaluating and managing risks in the following chapters.

5.2 Assessing risks to potable water supplies:- some past approaches

Many of the studies are site-specific assessments with very little attention paid to the development of a generic approach or structured methodology. Here, six risk assessment case studies taken from the water industry are compared to the four stage general framework described in Chapter 4 (see Figure 4.8). This categorisation of previous approaches allows the identification of common themes and the potential of such techniques to be evaluated.

Table 5.1 summarises how the methodologies are partitioned into the four stage approach and identifies the main techniques used in each stage.

Table 5.1 Techniques employed in risk assessments and their relation to the general risk assessment methodology described in Chapter 4 (for a selection of drinking water quality studies).

Reference	Purpose	Hazard Identification	Hazard Estimation	Risk Evaluation	Risk Management
Cole et al (1988)	Pollution risk assessment of surface water intake catchments	<ul style="list-style-type: none"> • "Assessment of sources of pollution" • examination of historical records • catchment inspections • visits to sites regarded as potential risks. 	<ul style="list-style-type: none"> • "Risk of pollution event" • evaluate pollution records • return periods estimated from historical records and national / generic statistics weighted by local inspections 	<ul style="list-style-type: none"> • time of travel & dispersion studies • comparison with maximum admissible concentrations at the intake site 	<ul style="list-style-type: none"> • "Risk control" • removal of hazards • pollution incident notification • river monitoring • intake & treatment works management recommendations
Baron (1989)	Pollution risk assessment of a surface water intake to predict the impact of proposed bankside storage	<ul style="list-style-type: none"> • site studies & surveys • discussion with local organisations and individual companies in the catchment 	<ul style="list-style-type: none"> • frequency estimation from historical records • summing of frequency estimates • pollution transport and dispersion modelling 	<ul style="list-style-type: none"> • comparison with MAC values set out in EC Directive 80/788/EEC on potable water quality 	<ul style="list-style-type: none"> • estimation of improvement offered by bankside storage scheme
Keller & Wilson (1992)	Potential Abstraction Risk Index (PARI): pollution risk assessment of industrial sites in surface water catchments	<ul style="list-style-type: none"> • field surveys of potential polluting sites • inventory of chemical stock holdings • assessment of flow regimes 	<ul style="list-style-type: none"> • calculation of maximum potential concentration of pollutant (based on quantity of pollutant; pollutant concentration levels; water volume affected and solubility of the substance) 	<ul style="list-style-type: none"> • comparison of maximum potential concentration to the acceptable concentration based on "Lethal Dose" mammalian toxicity values and average water consumption figures (to give PARI rating) 	<ul style="list-style-type: none"> • site-specific recommendations to prevent chemical releases at their source, remove pollutants in the river, or remove pollutants by treatment

Table 5.1 Continued.

Reference	Purpose	Hazard Identification	Hazard Estimation	Risk Evaluation	Risk Management
Eddowes (1995) [‡]	Pollution risk assessment of industrial sites in surface water intake catchments	<ul style="list-style-type: none"> • "Hazard Identification" • site visits • audit of facilities, processes, storage & transport arrangements 	<ul style="list-style-type: none"> • assessment of maximum spill size • examine flow conditions • estimate failure frequencies from generic data 	<ul style="list-style-type: none"> • compared to estimated acceptability criteria (based on toxicological studies) 	<ul style="list-style-type: none"> • on-site mitigation measures • pollution incident communication recommendations
Pollard et al (1995) [†]	Quantitative risk assessment of groundwater contamination from road accidents	<ul style="list-style-type: none"> • "Hazard identification" • sensitivity analysis (of traffic groupings) • field survey of aquifer catchment area 	<ul style="list-style-type: none"> • national transport statistics • probability estimated from Poisson distribution • deterministic estimates of transportation and fate of spilled substances 	<ul style="list-style-type: none"> • comparison with drinking water regulations and comparison to benchmark values in comparable industries (civil engineering & insurance) 	<ul style="list-style-type: none"> • production of management plans to reduce the impact of specific spill scenarios
WRc (1996)	Groundwater risk assessment for the protection of potable supplies	<ul style="list-style-type: none"> • "Catchment definition" • identify hazards (catchment audit) • identify catchment hydrogeology • identify protection / abatement technology 	<ul style="list-style-type: none"> • "Risk of pollution event" • evaluate water quality • assess time of travel & dispersion • assessment of historical data 	<ul style="list-style-type: none"> • "Pollution evaluation" • damage analysis • comparison with toxicological studies • comparison to drinking water regulations 	<ul style="list-style-type: none"> • "Risk abatement / prevention" • revised monitoring strategies • pollution incident warning systems • response protocols

"Titles in quotation marks represent the terminology used in the study"

[‡] Three levels of assessment are described in Eddowes (1995). The information in the table refers to the Extended Risk Assessment (ERA) which is the most comprehensive.

[†] See also Morrey et al (1995)

The hazard identification stage of these studies has commonly involved a combination of field or site visits and audits, and the creation of an inventory of potential hazards. Study of historical data are also used to give an indication of the potential problems to be faced in a catchment. Historical data are also used in the hazard estimation stage, often combined with model-based determinations of flow regime and pollution transport.

Hazard estimation techniques include the extrapolation of estimates from historical frequency data (Cole *et al.*, 1988; Baron, 1989; Eddowes, 1995; Pollard *et al.*, 1995; WRc, 1996), thus assuming that the factors affecting water quality remain relatively constant. In contrast, Keller & Wilson (1992) combine scenario-specific estimates with known constant values such as solubility.

In evaluating risks to the quality of drinking water, the above studies use a variety of techniques to compare predicted or calculated values to levels of acceptability. Acceptability in terms of drinking water pollution is not formally defined in the water industry, but the drinking water quality regulations are commonly taken to be the major benchmark for the comparison of risk estimates. Cole *et al.* (1988), Baron (1989) and Pollard *et al.* (1995) all compare estimated levels of water quality parameters to the relevant drinking water regulations. Keller & Wilson (1992) and Eddowes (1995) compare their estimates to toxicological values extrapolated from mammalian lethal doses or the level of 'no adverse response' in humans. WRc (1996) compare their estimated values of various parameters to both toxicological values and drinking water regulations. The novel approach of creating a risk index to interpret the ratio of the maximum predicted value to the maximum acceptable value by Keller & Wilson (1992) provides an immediate evaluation of risk significance. Such an approach greatly facilitates the communication of risk assessment findings, especially to those not familiar with the specifics of toxicology or water quality regulations.

Pollard *et al.* (1995) also evaluate risks in terms of their frequency (return periods of occurrence). Again no benchmark levels of acceptability exist within the water industry in general, but the authors compared their findings to benchmarks from other application areas (civil engineering and insurance), finding their estimated risk probabilities to be greatly in excess of the 1 in 100 derogation events commonly used as a benchmark in other studies. The issue of acceptability should be addressed by all organisations in the water industry. Conducting risk assessments using a consistent generic approach will assist in such discussions by providing more examples of the kinds of values produced by 'typical' assessments. The findings of this research can therefore be used to suggest the levels at which risk estimates are commonly found and identify potential benchmark values.

The lack of agreed levels of acceptability also means that the level at which management actions are recommended varies between studies. Some researchers (e.g. Cole *et al.*, 1988; WRc, 1996) suggest very general actions showing little detail of how these should be carried out.

For example, statements such as ‘prevent pollution reaching the river’ are put forward with little information about methods to successfully carry this out, or the resultant impact on risks. Alternatively, project-based assessments often result in very specific recommendations for management action (e.g. Eddowes, 1995).

Despite the lack of detailed, generic risk management recommendations in the six assessments investigated, the improved understanding of catchment processes that can be gleaned from a risk assessment presents a valuable opportunity to develop effective catchment management strategies to optimise water quality and yield. This improved knowledge can therefore provide opportunities for pro-active risk management through catchment control activities.

Four of the above case studies (Baron, 1989; Cole *et al.*, 1988; Keller & Wilson, 1992 and Eddowes, 1995) have particular relevance to this research and are investigated in more detail below.

Cole et al. (1988) – Pollution risk assessment of surface water intakes

Cole *et al.* (1988) conducted what can be considered as the first example of published research that recommends a framework for the assessment of pollution risks to surface water intakes rather than presenting a risk assessment case study. Their work remains one of the few published papers in this field, despite the increasing popularity of risk-based work and awareness of water quality issues.

As with other applications of risk assessments, Cole *et al.* (1988) apply regional and national statistics to the prediction of pollution events. The authors recommend using a combination of the examination of historical records describing water quality, pollution incidents and effluent discharges, together with independent examinations of the catchment area to determine site-specific weightings and hazards. The authors’ approach to hazard identification takes an important step rarely seen in other studies (e.g. Keller & Wilson, 1992 and Eddowes, 1995) in that they consider potential hazards from both point and non-point sources. This is extremely important when considering upland water supply catchments such as those in Yorkshire with many potential non-point sources of pollution (see Chapter 2).

In preparing estimates of hazard frequency, Cole *et al.* (1988) recommend extracting values from annual reports of the water authorities (as they were at the time) and national reports on pollution incidents, road traffic accidents and landfill sites.

Cole *et al.* (1988) also describe the use of tracer experiments to predict the time of travel and dispersion of pollutants. Initially used in hazard estimation, the results of these experiments were then used in the subsequent evaluation stages where predicted values are compared to maximum admissible concentrations (MACs) at the intake site.

Despite the potential of the hazard identification techniques used by Cole *et al* (1988) to highlight unforeseen hazards, the case study described focussed on those parameters routinely monitored in the river, and criticised the lack of data on parameters such as hydrocarbons and pesticides. This dearth of information meant the methodology was not able to identify whether such substances had previously been found in the river, or prepare probabilistic assessments of their occurrence. No account was taken of parameters and substances not routinely monitored in the river. The study was based on EC MAC values stipulated in the EC Directive on the quality of water to be abstracted for potable supply (75/440/EEC), as national legislation to adopt these standards had not been enacted in the UK at that time. Improved monitoring following the adoption of both The Surface Water (Classification) Regulations 1989 (HMSO, 1989b) and the Water Supply (Water Quality) Regulations 1989 (HMSO, 1989a) should help to facilitate both hazard identification and estimation from historical records.

A number of general risk management recommendations are proposed by the authors such as:

*“ - develop procedures to minimise the likelihood of polluted water being abstracted.
- to monitor key aspects of river water quality.”*

(Cole *et al*, 1988 p.608)

More specific recommendations include the establishment of an efficient communication system for the notification of pollution incidents in the supply catchment.

Carrying out a generic risk assessment can aid communication by identifying incidents and locations of primary concern to abstractors. Initiatives such as the Environment Agency free emergency telephone line will also be beneficial to the incident reporting and communication process. The risk management recommendations made by Cole *et al* (1988) were very general in nature although they do highlight many of the issues to be considered in reducing risks in intake catchments.

Baron (1989) – Assessment of the frequency of pollution incidents affecting the Elvington river intake

Baron (1989) is an example of a site-specific case study risk assessment. The project contributed to an operational decision on bankside storage at a river intake by assessing the pollution risks in the intake catchment. The extent to which the storage scheme reduced these risks was then identified. Baron (1989) considered a risk purely as the frequency of a derogation event occurring. A derogation was defined as a failure of the EC MAC value (EC Directive 80/778/EEC) for a particular parameter in untreated river water at the intake site.

Potential sources of contamination were identified from historical pollution incident data for the catchment and through extensive catchment surveys. This involved collaboration with local pollution prevention staff and detailed questionnaires distributed to industrial sites in the catchment, a task which would involve considerable work if conducted for a large number of intake sites or in a large catchment area. Point sources (industrial sites only) were then evaluated using the ADZ computer-based water quality model. A combination of the amount and location of polluting material and knowledge of the river flow regime allowed the calculation of pollutant concentration and duration at the intake site. Sources which could potentially result in a contamination above the MAC values were then subject to a probabilistic risk assessment. The frequency of a pollution incident occurring was estimated by combining estimates of operational failures gleaned from previous studies and generic data.

Baron (1989) briefly considered pollution risks from non-point sources of pollution in the catchment. Hazards posed by agricultural activities were identified and estimated by ADAS (the Agricultural Development and Advisory Service) from approximations based on stock holdings and crop figures. These estimations involved applying 'assumed' usage and storage rates to the local data, thus providing an indication of the potential hazards present. Only the most widely used pesticide varieties were considered and no account was taken of chemicals used on the extensive areas of vegetable crops. Risks from transport were assessed by a small traffic survey of the local major roads. Pollution from 'miscellaneous sources' was estimated to be between 0.032 (1 in 31 years) and 0.5 (1 in 2 years), although no explanation of the methods used or sources investigated is given.

The final assessment of risk is described by summing the frequency of occurrence of each of the categories of pollution. This therefore compounded any uncertainties resulting from the variety of data sources used. Each frequency value was compared to an assessment of only those risks that would cause the intake to be closed for more than two days (the number of days supply in the proposed storage system) to evaluate the impact of the bankside storage scheme on supply security. The frequency of intake closure was expected to be reduced from three per year to once every three years following the completion of the scheme.

Baron (1989), as other studies (Keller & Wilson, 1992; Eddowes, 1995), restricted the majority of the assessment to 'quantifiable' industrial sites and consideration of non-point sources was especially poor. The study did not consider risk management options to reduce the risks in the catchment and focussed purely on engineering a solution to reduce the impact on the distribution network. This illustrates the re-active approach to water quality management discussed in Chapter 2 (Section 2.5.1).

Keller & Wilson (1992) - Potential Abstraction Risk Index (PARI)

The PARI (Potential Abstraction Risk Index) originally developed by Lamb & Keller (1987) and refined by Keller & Wilson (1989; 1992) has been used to rank the potential risk of chemical installations situated in river catchments that contain water supply intakes. As with Baron (1989), only those with the potential to exceed a predetermined value at the intake (in this case a PARI rating >1) are investigated further.

The PARI methodology is based on the worst-case scenario, in that the total stock of a site is assumed to enter the watercourse, undergo no physical or chemical degradation in the river and be abstracted directly into supply. Only the peak storage values of chemicals are considered, taking no account of fluctuating stock levels. The hazard identification stage of this approach, as with Baron (1989), therefore requires extensive field surveying or access to accurate stock records and is limited to the assessment of existing industrial sites. Such an approach may be suitable for generalised assessment of risk from industrial premises, for example over the whole of a supply company operating area, given access to vast quantities of (potentially commercially sensitive) information, but takes little account of the many water quality problems seen in upland catchment areas.

The risk posed by a site is evaluated by calculating the pollution abstraction risk index (PARI) value. The PARI is defined as the ratio of the maximum potential concentration to an acceptable concentration derived from the substances' toxicity. The maximum potential concentration takes into account the volume of water likely to be affected and substance solubility. The acceptable concentration is based on the lethal dose (LD) value of the substance, the average body weight of the receptor, the amount of water consumed and a safety factor (Keller & Wilson, 1992). A PARI rating of greater than unity (one) indicates that a hazard to human health from drinking water quality exists.

In an unusual step to accommodate the hazard posed by substances that are not necessarily toxic, but may impart undesirable tastes, odour or appearances to drinking water, two forms of the PARI system have been developed. The PARI Hazard or PARI(H) is based on the toxicity considerations discussed above, and the PARI Acceptability or PARI(A) is based on the organoleptic properties of a substance. In calculating the PARI(A) the LD 50 (mammalian) value is replaced by the lowest known organoleptic value and the safety factor is removed. Thus, the PARI(H) considers direct threats to health and the PARI(A) relates to the acceptability of the water for drinking and food processing.

Keller & Wilson (1992) therefore go beyond many other assessment studies by considering impacts on the appearance, taste and odour of the water as well as toxicity (although these are also considered where the risks are evaluated against the drinking water regulations), but again they only consider worst-case scenarios from industrial point sources in the catchment area. No assessment is made of non-point source pollution risks. Little consideration is given within the PARI methodology for risk management actions, either through the provision of recommendations or iterative re-assessments to monitor changes in the risks present.

Eddowes (1995) - Pollution Risk from Accidental Influxes into Rivers and Estuaries (PRAIRIE)

Risk from substances accidentally introduced to rivers and controlled waters are of concern to the Environment Agency (formally the domain of the NRA). The establishment of Water Protection Zones under Section 93 of the Water Resources Act 1991 also requires an established manner of quantitatively assessing the risk of operational plant and facilities (Fryer & Nixon, 1995). In an effort to protect human health from risks associated with the supply of unwholesome drinking water, the former NRA (in collaboration with AEA Technology), developed a multi-level risk assessment tool to assist in the creation of Water Protection Zones. PRAIRIE is intended to assess the risks posed to drinking water abstraction points as a result of an accidental discharge into a watercourse from operations at an industrial site or plant.

Like Keller & Wilson's (1992) study, this procedure was developed for the River Dee (Wales), where significant amounts of high quality historical data are available. Information about the storage of chemical substances within the proposed Water Protection Zone, and previous pollution incidents were particularly important in the development of the approach. Again however, PRAIRIE is only used to assess the risk of an existing industrial site and no assessment of non-point sources is conducted. Thus it can be considered a more complex, but fundamentally similar approach to the PARI methodology.

Hazard identification involves site visits to industrial installations in the catchment (or proposed water protection zone) to obtain information on chemical storage facilities and stock levels. It is then assumed that the total chemical store on the site is released at the 95 percentile flow (the volume at or above which the discharge is maintained in the river for 95% of the year) and the concentration at the nearest downstream intake calculated using the PRAIRIE computer model. PRAIRIE (based on a combination of Manning's formula and the DYNUT aquatic dispersion model) represents the spatial and temporal dispersion of a pollution incident downstream to assess the concentration and time period of a pollutant at a specified downstream point (Welsh, 1992). This forms the initial screening stage of the assessment, during which sites shown not to contain sufficient material to contaminate the intake are removed from the assessment. The acceptability of these values is evaluated against 7-day and 24-hour SNARLS (Suggested No Adverse Response Levels) and Lethal Concentrations (LC₅₀ and LC₅) at the intake site.

The second stage of the approach involves a probabilistic assessment of contamination occurrence at a site. This medium level risk assessment uses general failure rates for the type of equipment on site, thus reducing the need for site-specific failure information and surveys. Again the calculated values were compared to the NRA acceptability criteria based on SNARLS and Lethal Concentrations.

Those sites and substances that are still considered to present an intolerable hazard to the nearest downstream intake are then subject to an extended risk assessment (ERA). The ERA takes into consideration site-specific data such as on-site mitigation and control measures, chemical changes in the river and the use of site-specific failure data. Again data are compared to the acceptability criteria in order to prioritise risk mitigation measures. This stage therefore requires detailed, site-specific data necessitating access to the site itself and the operating company's records.

The PRAIRIE study does not consider incidents not arising from non-industrial operations (e.g. agricultural sources) or diffuse pollution sources outside of an industrial site as they are not subject to the regulations pertaining to the establishment of a water protection zone – the initial aim of the methodology. Eddowes (1995) does not suggest generic risk mitigation scenarios due to the site-specific nature of the approach.

Summary

This section has highlighted some of the approaches used in past studies but has also shown that none of the methodologies is suitable for generic applications to rural upland catchments. Cole *et al.* (1988) is probably the only published research to date that considers the methodology of assessing risks rather than merely describing a case study assessment. However, the actual structure of the methodology was not defined in a form that could be easily transferred for application to other intake sites. Only limited assessment was made of the physical environment of the catchment area and no consideration was given to characteristics such as soil type, land cover, topography and their effect on water quality. This research will therefore enhance the work of Cole *et al.* (1988) by formally evaluating and describing generic techniques for intake risk assessment. It will also incorporate the use of novel technologies (GIS) to manage data describing the physical environment and facilitate the risk assessment process.

There has been considerable research into the application of GIS technologies to the prediction of water quality and quantity (see Chapter 3) although, as yet there have been no specific applications of GIS to pollution risk assessments of surface water intake sites. The intrinsic capacity of geographical information systems (GIS) to store, analyse and display such data makes them ideal tools for assisting in such assessments and therefore form the basis of this methodology, as described below.

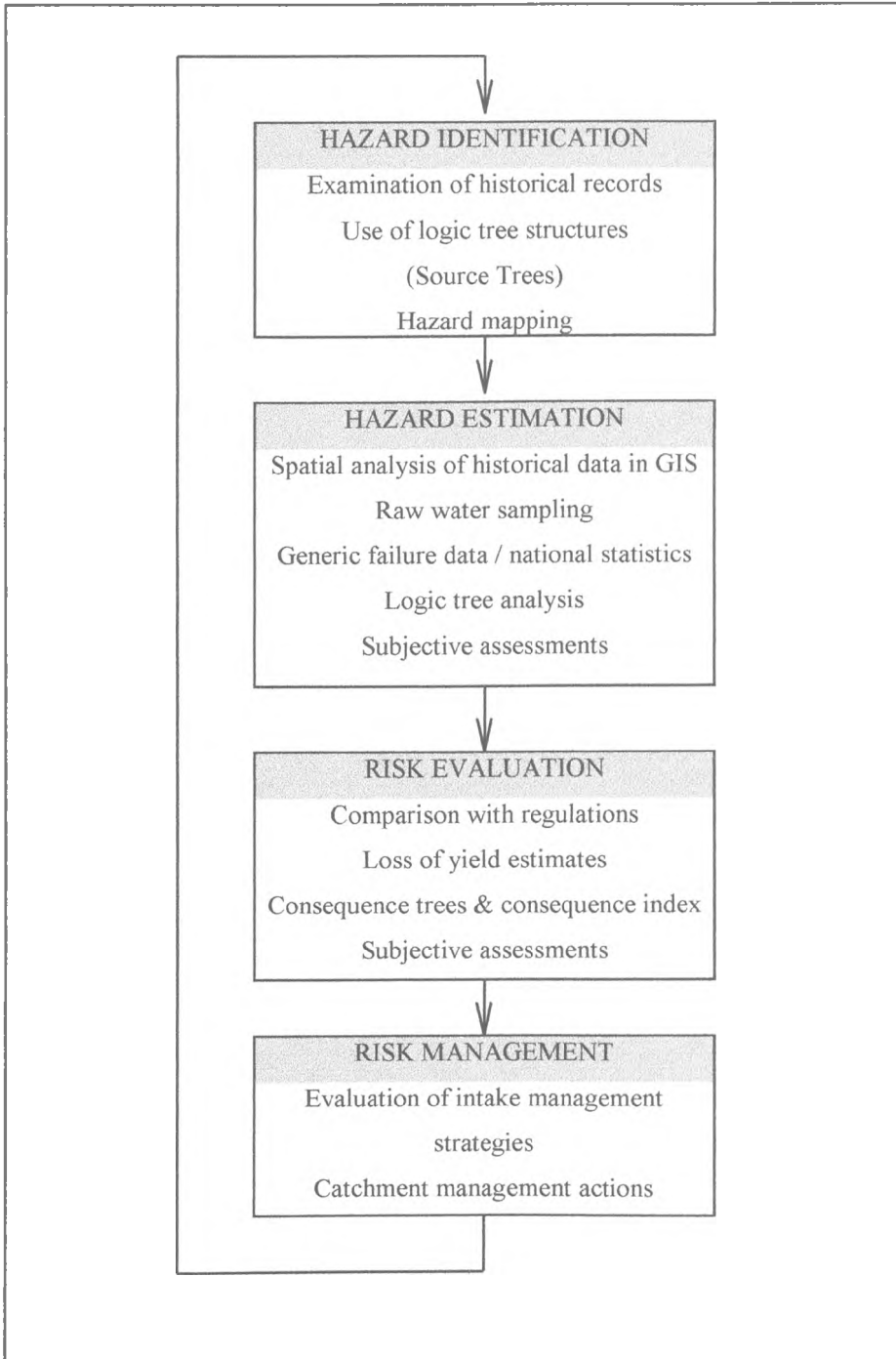
Only Cole *et al.* (1988) and Baron (1989) contain any consideration of non-point sources and here their assessment is particularly poor. The research of non-point sources in general from a risk assessment perspective is grossly lacking in the current scientific and hydrological literature.

All the hazard identification techniques described above rely heavily on the availability of historical data or intensive catchment field surveys, thus requiring considerable effort if assessments were to be carried out for several catchment areas. No use is made of automated hazard identification techniques. Progress in GIS development and increasingly available digital spatial data allow areas of land to be searched for potential water quality hazards using digital data and spatial queries (Foster *et al*, 1997). This removes the need for extensive historical data requirements or field surveys. GIS have the potential to assist in the other stages of the assessment, for example, in the spatial analysis of pollution incident locations and modifying catchment information to predict the impact of risk mitigation measures. The potential of such approaches are explored in this study

5.3 The Risk Assessment of Supply Catchments And Land (RASCAL) methodology for assessing pollution risks to water supply intakes:– theoretical framework

Consideration of many of the approaches taken in environmental risk assessment has lead to the definition of a new methodology for assessing the risks to surface water intakes. In the assessment and management of risks associated with the contamination of drinking water, the key issues are the protection of human health and the efficient use of water resources. This focuses the attention of the study on the risk of contaminated water being present at the point of abstraction (the river intake), as proposed by Cole *et al* (1988) and Keller & Wilson (1992). Such a methodology can also be used to assess the impact of contamination on the natural environment in and around the river prior to abstraction. The RASCAL approach is similar to a traditional ‘technical risk assessment’ in that it will involve elements of actuarial assessment (a basic estimate of the relative frequency of occurrence averaged over a time period), toxicological and epidemiological assessments (where causal relationships are explored and modelled) and probabilistic assessments (where the probability of individual features of a system are predicted and combined, given insufficient information on the operation of the system as a whole).

Figure 5.1 shows the interrelation of the 4 stage RASCAL methodology, together with examples of the techniques to be used in each stage. The approach shown in Figure 5.1 is fundamentally a probabilistic one, but the analysis involved in any one of the different stages may be quantitative, semi-quantitative or qualitative, depending on the nature of the water quality parameter under consideration. This is in keeping with recommendations made by acknowledged authorities in applied risk assessment and water management such as Banyard (1995). The application and development of this methodology is seen throughout the remaining chapters of the thesis. The different stages of the RASCAL risk assessment process are outlined below.

Figure 5.1 Fundamental elements of the RASCAL process

5.3.1 Hazard Identification

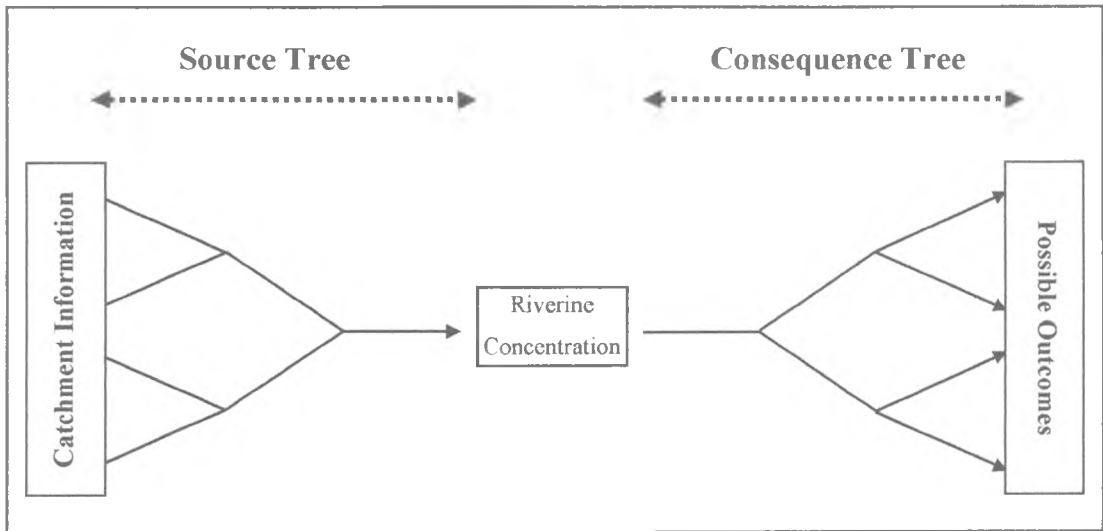
Hazard identification involves the process of looking at the water quality history and the catchment characteristics and making a decision as to the potential hazards to water quality. The legislation governing the quality of water abstracted and distributed for drinking water specifies Prescribed Concentration Values (PCVs) for several parameters (HMSO, 1989a; HMSO, 1989b). Analysis of the performance of the river water quality against such values can be used to give an indication of the common sources of contamination for a particular supply source. The improved reporting of incidents following privatisation of the water industry in England and Wales and creation of the NRA, has led to more widely available historical data concerning the nature and frequency of pollution incidents (see for example, National Rivers Authority, 1995; Environment Agency, 1996). The preparation of catchment management plans and LEAPs (Local Environment Agency Plans) has also improved the availability of catchment-specific data, although rarely in sufficient detail for risk assessment purposes. Pollution incident data, both national and catchment specific may also assist in the identification of potential contaminant sources (Chapter 2).

Catchment auditing and spatial analysis in a geographical information system (GIS) will be used to identify hazards in the catchment through the use of known relationships between catchment characteristics and water quality (e.g. Kay & Stoner, 1988; Mitchell & McDonald, 1992; Hornung *et al*, 1994; Mitchell & McDonald, 1995). Logic trees will be used to combine the physical characteristics resulting in potential pollution sources and therefore predict their spatial distribution using GIS (i.e. they form the basis of the creation of hazard maps).

Fault trees will be used in the identification of causal activities in the catchment that may result in an undesirable concentration of a particular substance reaching the intake. Event trees are then used as one method of assessing the significance of the consequences of such concentrations at the supply intake. The terms *Source Trees* and *Consequence Trees* respectively, are more applicable to their use here and are therefore used in preference to the usual fault and event tree titles. Using the terminology commonly applied to these tree structures, the *root* of the diagram is representative of the riverine concentration in each case and the *leaves* determine the catchment information or GIS data needs for the Source Trees and possible outcomes for the Consequence Trees. Combinations of fault and event tree type structures are often referred to as cause-consequence diagrams (Lees, 1980; Beattie & Anderson, 1996).

The schematic basis of these tree structures is shown in Figure 5.2. The use of such Source Trees combined with hazard mapping is the primary method of hazard identification in the RASCAL methodology.

Figure 5.2 Schematic logic tree for risk assessments of potable water supply intakes



The tree structures are inherently flexible and can be modified according to the level of understanding of the processes involved. For example, the configuration of the structure will vary between the categories of point, quantifiable non-point and unquantifiable non-point pollution sources (these may in turn lead to quantitative, semi-quantitative and qualitative results). Careful construction of the logical structure describing a process may allow common-cause elements to be highlighted. The preparation of such trees for hazard identification stage is a fundamentally important part of the whole risk assessment as it necessitates an open minded view of the potential pollution hazard scenarios in the catchment and may therefore highlight problems previously unidentified

The output from the creation of the Source Trees will be used to model catchment relationships in the GIS. Hazard maps will be created, identifying potential water quality hazards in the intake catchment. As these maps will be based on information from historical events and the characteristics of a catchment that may result in a particular water quality problem, their validity will be investigated using raw water sampling data.

5.3.2 Hazard Estimation

The calculation of hazard probability may combine the use of historical data, logic trees and spatial analysis of catchment characteristics using the GIS.

Cole *et al* (1988) recommend using historical data to determine hazard probability in supply catchments but stress the importance of catchment specific surveys and the incorporation of local statistics to qualify the national averages that are used. Care must be exercised in the application of this approach to a generic methodology as pollution incident data is not widely available for all catchment areas.

Where pollution incident data is available for the study catchment, the frequency of occurrence of these incidents can be used to give an indication of the probability of point and non-point source pollution hazards being realised. Geo-referenced pollution data can be used to do this in a GIS. The frequency of occurrence in discrete spatial units (e.g. catchment or sub-catchment areas) can then be determined. The frequency of individual parameters exceeding the regulatory levels can also be used to predict hazard probability from existing records, but is dependant on the raw water sampling regime in place.

Spatial statistics obtained from analysis in the GIS, together with known relationships between catchment characteristics and water quality can also be used to predict the frequency of hazard occurrence. It is beyond the scope of this study to determine absolute values of stream water chemistry for all parameters concerned, although a number of studies (Boon *et al.*, 1988; Kay & Stoner, 1988; Mitchell & McDonald, 1992; Heal, 1996) have used regression techniques to predict stream water quality from the spatial distribution of catchment characteristics. It is also important to note that risks may be realised from either discrete events or from a continuous process and the probabilities can therefore either be additive or multiplicative. This is extremely important when considering risk probability, especially for water quality where many parameters are interdependent. The use of logic trees in the estimation of probability can potentially address this problem by identifying common cause relationships. The probability values assigned to the branches of the Source Trees that are used to assess hazard frequency can be weighted in terms of hydrological factors such as the distance and time of travel upstream of the intake site. Additional raw water sampling (Chapter 8) may also be used to create estimates of hazard frequency.

Where individual point sources are considered, generic failure data will be used, thus facilitating the systematic application to other catchment areas. Where site-specific data is widely available (and therefore accessible for other catchments) this will be used in preference to generic or national data sources. In the event that quantitative assessments, such as those described above, cannot be made, subjective assessments of frequency will be employed.

5.3.3 Risk Evaluation

No predetermined levels of risk (either acceptable or unacceptable) have been uniformly agreed by the UK water industry (Pollard *et al.*, 1995). Target levels for performance (not including the water quality regulations mentioned above) refer to supply quantity and not quality. Morrey *et al.* (1995) and Pollard *et al.* (1995) suggest a benchmark of acceptable risk to be around 1 in 100 derogation events per intake per year as being comparable to other engineering and insurance studies. In such cases, a derogation or risk occurrence can be taken as a failure of the drinking water regulation standards at the point of abstraction. Discussions with water supply managers have indicated that zero derogations are desired, but the impacts on supply are most informative if expressed in potential loss of yield resulting from intake closure as well as failure of the drinking water quality regulations.

For water supply intakes not directly at risk from an industrial installation, the HSE 'acceptable' level of risk is not applicable as this is specifically designed for exposure relating to industrial installations only.

Risks to water supply intakes are therefore best evaluated in terms of failures of the drinking water regulations, loss of yield and potential impacts on public health. Values can be compared to two major pieces of legislation governing the quality of drinking water that is abstracted, treated and distributed for public supply, against which risks can be evaluated. The Surface Waters (Classification) Regulations specify the quality standards of the water that must be maintained given the treatment facilities in place and are based on the European Community Directive 75/440/EEC (HMSO, 1989b). They theoretically take account of the expected efficiency of the treatment processes. The Water Supply (Water Quality) Regulations determine the quality of water required for potable supplies after treatment (HMSO, 1989a).

These regulations take into consideration both health and aesthetic considerations and are the primary legislation driving the supply activities of the water undertakers. The consequence of a hazard can therefore be measured against a failure of these regulations as they may result in financial costs for the water undertaker (due to increased treatment costs or fines imposed for regulatory non-compliance) or public health impacts for consumers at the tap. This approach is similar to one of the few quantitative risk assessments carried out on water supply abstractions (albeit a groundwater source) to date described by Morrey *et al* (1995) and Pollard *et al* (1995).

The use of *treated* water standards to assess risks in *raw* waters does suggest a number of problems. Firstly it assumes that the water in the river is of drinking water standard which is unlikely, but consequently this approach results in a large 'safety factor' in the consideration of (Baron, 1989; Pollard *et al*, 1995). Secondly, it assumes that the current legislation is comprehensive in terms of the toxicological parameters and standards set. The regulations are soon to be updated (see Section 2.2.1, Chapter 2), but the current standards do cover any substance that is considered to prevent the water from being 'wholesome' i.e. contains no element, organism or substance detrimental to public health (HMSO, 1989b). Using the drinking water regulations allows the financial and legal consequences of risks to be assessed as past experiences of regulatory failures can give some indication of the level of financial penalty. As new legislation is enacted the methodology can be easily updated to take account of improved knowledge of the public health impacts of drinking water and the new standards of service to which suppliers have to conform. Thus, in this approach the need for transparency to changes in regulations identified in Chapter 2 (section 2.2.1) is achieved.

The potential consequence of sources of contamination can potentially be assessed using a modified version of the PARI method defined by Keller & Wilson (1992). Instead of using the LD₅₀ concentration as the acceptable concentration, the standards defined by the UK regulations can be used and compared to the predicted concentrations at the river intake to create an index (ratio) value.

Loss of yield estimates can be based on maximum abstraction quantities and the predicted impact on the supply network. If insufficient water quality data exist to carry out quantitative assessments, such as those described above, the parameters will undergo a qualitative (subjective) assessment of risk

5.3.4 Risk Management

Risk management involves identifying and carrying out risk reduction actions and should include regular monitoring and re-assessment. The risk management stage therefore has the important role of ensuring that the risk assessment process becomes iterative (hence the feedback loop seen in Figure 5.1). It is important to set targets for management activities to achieve, to assess the performance of activities against these targets and to carry out regular re-assessments of risk in the catchment.

Two types of risk management options can be considered in studies of supply intakes. Firstly the management of the intake itself can be evaluated and recommendations put forward to reduce the potential impacts of risks to supply. Secondly, catchment management options to reduce the initial hazards can be suggested. This second approach moves away from the re-active approach commonly taken in previous studies (e.g. Baron, 1989) and will result in pro-active management actions to reduce the risks to surface water intakes. The impact of these actions can also be predicted using GIS modelling and re-assessment. This potentially allows the location and nature of risk management options to be optimised.

5.4 Conclusions

At present no widely accepted catchment-scale methodology for the broad assessment of pollution risk to potable water supply intakes exists. Practical applications of risk assessment techniques have been conducted, but are mainly carried out with respect to individual industrial installations within a catchment area. It is the aim of this research to extend beyond these past approaches to assess pollution risks from all hazards in a catchment and to develop a framework for application to the water supply catchments in Yorkshire. Unlike many previous approaches, the methodology introduced in this chapter (and developed throughout the thesis) will allow the assessment of both point and non-point sources of pollution. The framework includes the use of Source and Consequence Trees (similar to the more common fault and event trees) in identifying hazards and evaluating their probability and consequences. The use of geographical information systems (GIS) throughout the risk assessment procedure is also introduced although this is described in greater detail in later chapters. The use of historical data (both generic and catchment specific) is identified as a major source of information, but raw water sampling and analysis are suggested to corroborate the inferences made from such data. Where no such data exists the combination of qualitative (subjective) methods of risk assessment are proposed.

Management actions for risk mitigation may include traditional re-active proposals for intake operation and treatment activities, but recommendations should focus on pro-active actions both for catchment management and intake operation.

The procedural framework defined this chapter will be used in the following sections of the research to identify and test a clearly defined methodology that can be used to assess the pollution risks to surface water public supply intakes.

Chapter 6

Hazard identification in the Upper Wharfe catchment (1): using historical data

6.1 Introduction

Hazard identification is the initial and one of the most important stages of the risk assessment process. This chapter describes the identification of pollution hazards in a water supply catchment using historical data.

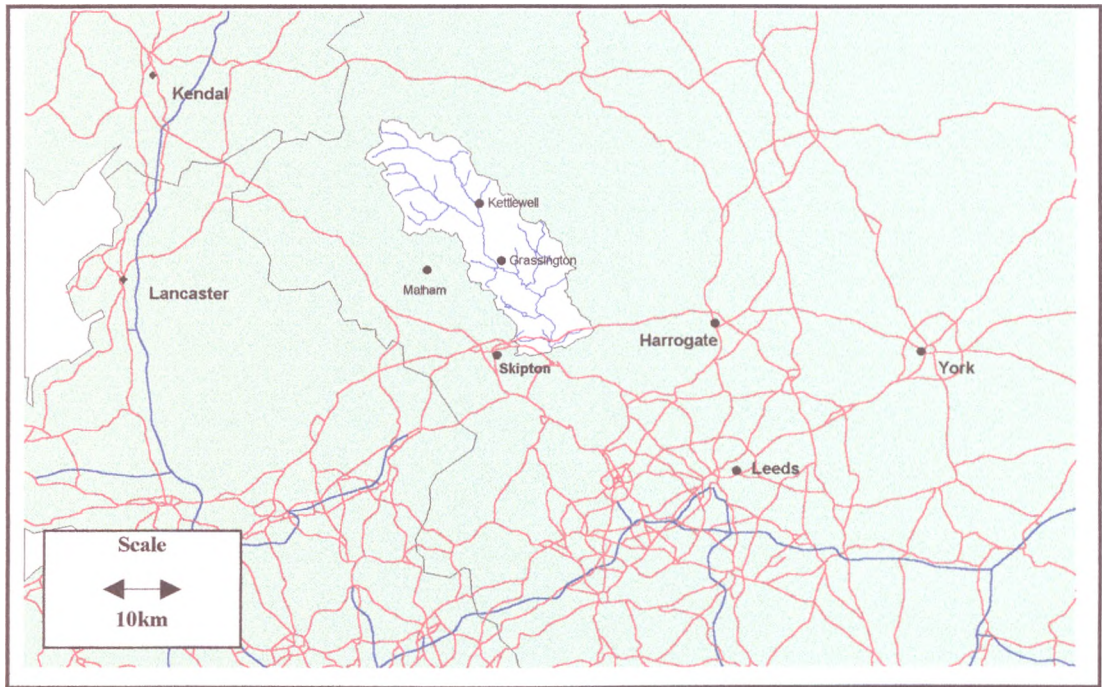
Section 6.2 introduces the study catchment, its physical geography, and describes how this area was divided into hydrological sub-catchments to facilitate the following investigations. Section 6.3 reports on the use of historical data to identify potential pollution sources, hence creating an initial checklist of possible hazards as proposed in Chapter 5. The characteristics of the individual sub-catchments are described as they form the fundamental drivers behind the potential pollution scenarios. Historical data describing water quality trends and pollution incidents are then used to identify potential problem issues within the catchment. These secondary data were combined with field surveys to audit potential pollution sources.

6.2 The Upper Wharfe Catchment

6.2.1 Physical characteristics

The River Wharfe rises close to Ribbleshead in the Northern Pennines and its mainstream is formed at the confluence of the Oughtershaw and Langstrothdale Becks at Beckermonds (Environment Agency, 1997c). The river then flows southwards past Kettlewell and Grassington, before turning east past Ilkley, entering the River Ouse 13km south west of York. The study area of this research is the Upper Wharfe catchment (above the Lobwood water supply intake, 9.5km east of Skipton (NGR: SE 0755 5190)), as shown in Figure 6.1.

Figure 6.1 Location of the Upper Wharfe catchment, North Yorkshire
(showing Major roads and selected settlements)



The area under investigation (shown above) upstream of the Lobwood intake, is approximately 416 km². The elevation of the land surface ranges from 80 to 700m above mean sea level (a.s.l.), although much of the area is more than 600 m a.s.l. The average annual rainfall varies from about 600 mm per year in the lower reaches to 2000 mm per year around the headwaters. The predominant geology of the area is Carboniferous Limestone, with areas of Millstone Grit in the southern and eastern reaches. Much of the catchment lies within the Yorkshire Dales National Park and contains several Sites of Special Scientific Interest (SSSIs) including parts of the river itself.

6.2.2 Hydrology of the Upper Wharfe catchment

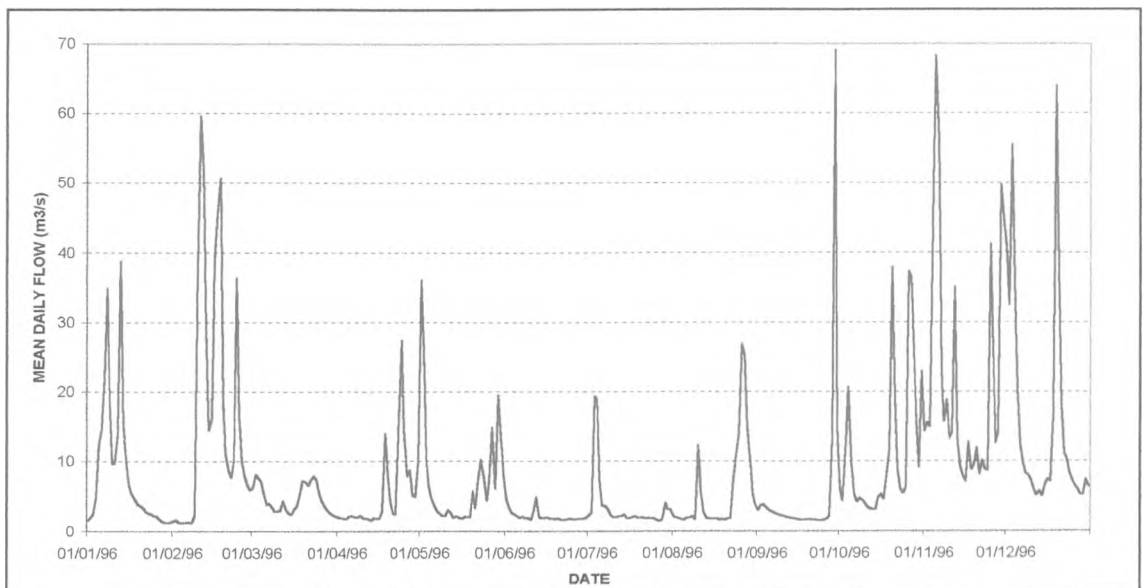
The geology and topography of the catchment area have a significant impact the hydrological response of the River Wharfe. The limestone sub-surface of the catchment affects both the baseflow and stormflow components of the River Wharfe's hydrograph. A considerable proportion of the Wharfe's baseflow discharge is directly fed from groundwater (Oakes, *Pers Comm*). Variations in discharge (upstream of Grimwith reservoir) are therefore heavily influenced by the level of the local water table and variations in groundwater flows.

In many catchment areas, the overland flow component of a rainfall event dominates the stormflow hydrograph. The fissured structure of limestone lithology in areas such as Wharfedale can also result in rapid throughflow with flow through the vadose (unsaturated) zone also contributing significantly to the rising limb of a hydrograph (Richards, 1982; Jennings, 1985). Such flows are also considerably quicker than soil or saturated zone throughflow (Kirkby, 1978; Hardwick & Gunn, 1996). The relationship between the hydrograph peak and water quality will be influenced by antecedent moisture conditions and groundwater and throughflow characteristics (Walling & Foster, 1975).

Subsurface flow patterns within the catchment are also influenced by the legacy of underground mine-workings (Environment Agency, 1997c) and flow pathways are therefore very difficult to predict. Further downstream, the baseflow of the river is partially regulated by the release of flow from Grimwith reservoir. This has the effect of ‘smoothing’ the baseflow hydrograph for the lower sections of the catchment, although storm events still result in rapid rises in discharge.

The steep narrow valleys coupled with rapid overland flow and flows through underground fissures cause the river to respond quickly to rainfall events. Thus, stormflow hydrographs for the river commonly have a steep rising limb. Numerous examples of this can be seen throughout 1996 in Figure 6.2 below. Hydrograph peaks typically lag six to twelve hours behind large rainfall events (Oakes, *Pers Comm*, Tarbotton, *Pers Comm*), with peak discharges of up to $70\text{m}^3\text{s}^{-1}$.

Figure 6.2 River Wharfe discharge hydrograph – Mean Daily flows during 1996 at Addingham Weir



(Source: National Rivers Authority flow data)

Despite the importance of groundwater contributions to the River Wharfe, the primary hydrological component considered in this study is overland flow (see Section 7.2.1). The overland flow process has the greatest potential to transport pollution hazards from the land surface of the catchment to the intake site. It is hazards situated on the land surface and within the soil layers of the catchment that can be influenced directly through catchment and land management practices.

The River Wharfe represents a major water resource in the Yorkshire region. There are two public water supply intakes in the catchment with a total licensed abstraction in excess of 250 megalitres per day (Mld). The catchment also contains Grimwith reservoir, the largest river regulating reservoir in the Yorkshire region, from which water is released to augment downstream abstractions. Following abstraction at the Lobwood intake, water is pumped to Chelker reservoir (1.5km away) where it is blended with water from the Barden reservoirs.

Some of the water is pumped to Silsden Treatment Works, treated (by coagulation, filtration, disinfection and pH correction), and distributed for supply in the small town of Silsden. The majority of the water is pumped from Chelker a further 19 kilometres to Chellow Heights Water Treatment Works (WTW) where it is blended with supplies from the Nidderdale catchments and Stubden reservoir. At Chellow Heights WTW, aluminium sulphate is added as a coagulant, followed by clarification (flocculation) in sedimentation tanks. The water is then filtered through ASG rapid gravity filters (containing anthracite, sand and gravel media), disinfected with chlorine and the pH corrected using lime. Since December 1995 the water has also been dosed with orthophosphoric acid to reduce plumbosolvency, controlling subsequent contamination by lead pipes. Once treatment is complete the water is distributed to customers in Bradford, Batley, Dewsbury and Cleckheaton, as well as supplying the Yorkshire Water grid system.

Due to the population of the areas supplied by Yorkshire Water's grid system, any contamination of the Upper Wharfe raw water supply has the potential to affect a large number of the company's domestic and industrial customers.

6.2.3 Division into sub-catchments

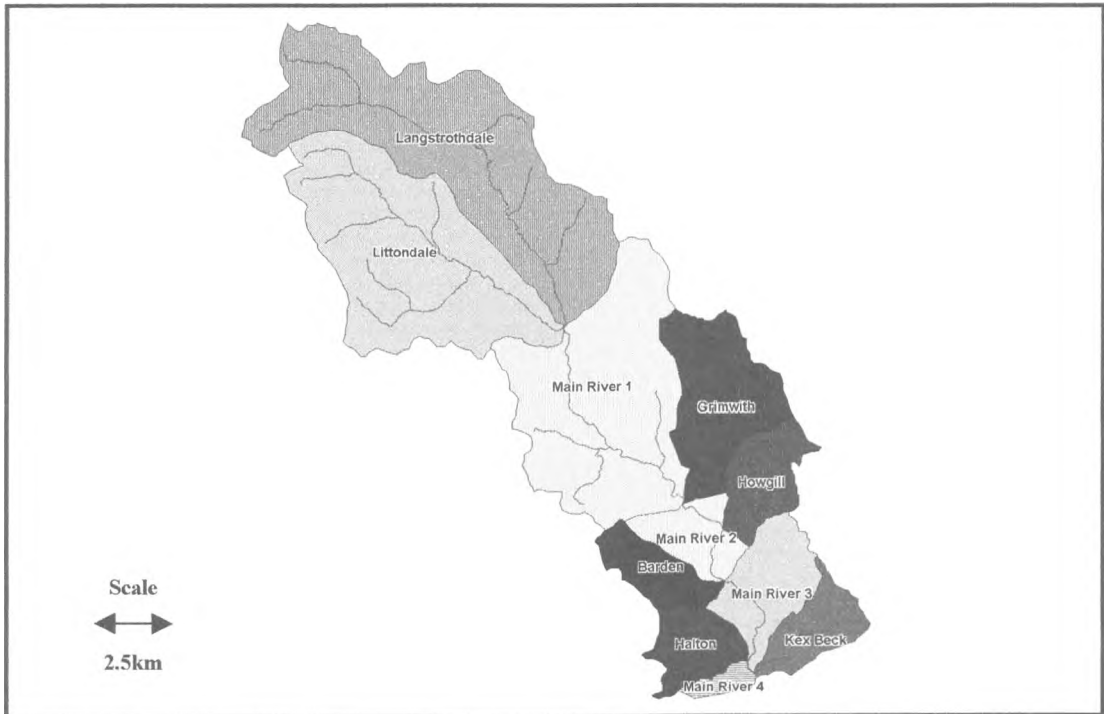
In order to facilitate the analysis of historical and digital data within the Upper Wharfe catchment, the area was divided into sub-catchments based on the major tributary streams. The use of these sub-catchments will also help in later investigations into relationships between catchment characteristics and water quality. This also allows the sub-division of large digital data files into sub-catchment specific data sets, therefore considerably reducing the processing times required for GIS queries, analysis and display.

The sub-catchment polygons were created using the WINGS on-screen digitising facility (Systems Options Ltd., 1995). The 1:50,000 scale river network and catchment boundary data (created by the Institute of Hydrology) were displayed over the 1:50,000 scale Ordnance Survey (OS) raster background maps and 1:50,000 scale contours. The major tributary streams were identified and the sub-catchment watersheds estimated from the raster map features such as stream networks and the contour features.

In the absence of surface slope tracing software such as the techniques described by McCormack *et al.* (1993) this manual approach was considered appropriate given the scale of the source data (1:50,000). The ability to align individual boundary links with mapped features and contour lines also enhances the process. Some inaccuracies in the resultant boundaries are inevitable as a result of errors in the source data and approximations resulting from the digitising. Local surface conditions and geology will also influence the flow pathways of the smaller streams (not shown on the 1:50,000 maps), although the sub-catchments should represent the major hydrological watersheds in terms of surface flows.

The eleven sub-catchment areas (named after tributary streams or geographical features within the areas) are shown in Figure 6.3.

Figure 6.3 Sub-catchment areas of the Upper Wharfe



The upper reaches of the catchment (Littondale and Langstrothdale) are characterised by pastureland and open moorland, with upland sheep farming dominating the land use. Further downstream, cattle grazing is more common and the catchments are traversed by several major roads (e.g. A65, A59). Figure 6.4 shows the land cover of the sub-catchments, based on the Institute of Terrestrial Ecology 25m Land Cover map of Great Britain.

Figure 6.4 Land Cover in the Upper Wharfe sub-catchment areas

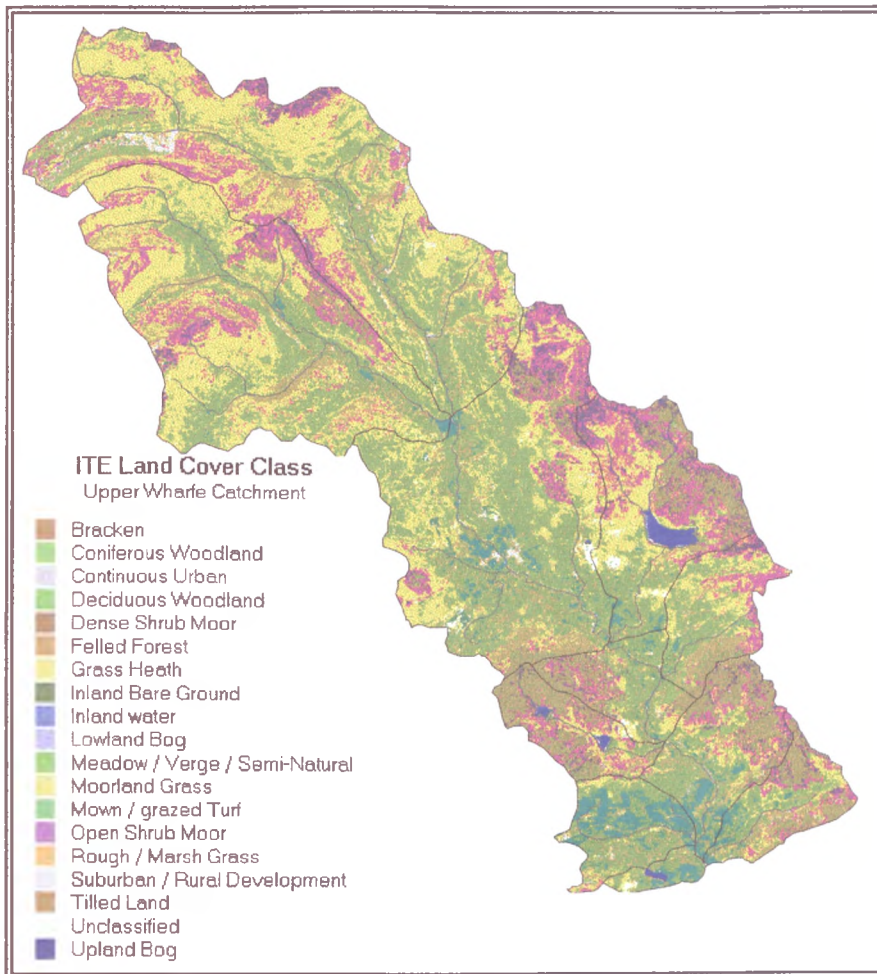


Figure 6.4 clearly shows the predominance of upland bog and bracken, moorland shrub and grasses, together with large areas of managed pasture and grassland. This is associated with the sheep farming seen in this area. Significant amounts of woodland are also evident in the upper reaches of the catchment area. In terms of pollution risk therefore, initial study of the land cover data suggest that water quality problems associated with forestry, upland soil characteristics and grazing animals may be experienced in this area. A summary of the physical characteristics of each of the eleven sub-catchment areas is given in Table 6.1 below.

Table 6.1 Physical characteristics of the 11 sub-catchments in the Upper Wharfe

Sub-catchment	Area (km ²)	Length of stream (km)	Drainage density (km / km ²)	Dominant geology	Dominant land use	Dominant soil type	Other major features (e.g. urban areas)
Barden	13.78	6.19	0.45	Millstone Grit	Moor	Peat	Upper & Lower Barden reservoirs
Grimwith	35.85	15.89	0.44	Millstone Grit	Moor	Surface water gley	Grimwith reservoir
Halton	14.52	9.19	0.63	Carboniferous Limestone	Pasture	Surface water gley	
Howgill	17.17	5.09	0.3	Millstone Grit	Pasture / moor	Surface water gley	
Kex Beck	14.26	5.56	0.39	Millstone Grit	Pasture / moor	Surface water gley	
Langstrothdale	102	41.76	0.41	Carboniferous Limestone, some Millstone Grit	Moor	Surface water gley	Kettlewell & Starbotton villages
Littondale	85.59	40.8	0.48	Carboniferous Limestone	Moor	Lithomorphic	Arncliffe village
Main River 1	84.52	26.42	0.31	Carboniferous Limestone	Pasture / moor	Lithomorphic	Grassington town
Main River 2	14.18	6.03	0.43	Millstone Grit	Pasture / moor	Surface water gley	
Main River 3	22.1	6.2	0.28	Millstone Grit	Moor / pasture	Surface water gley	
Main River 4	3.66	0.57	0.15	Millstone Grit	Pasture	Surface water gley	Chelker reservoir

Further details of how the physical characteristics of these sub-catchments relate to water quality are given in later chapters.

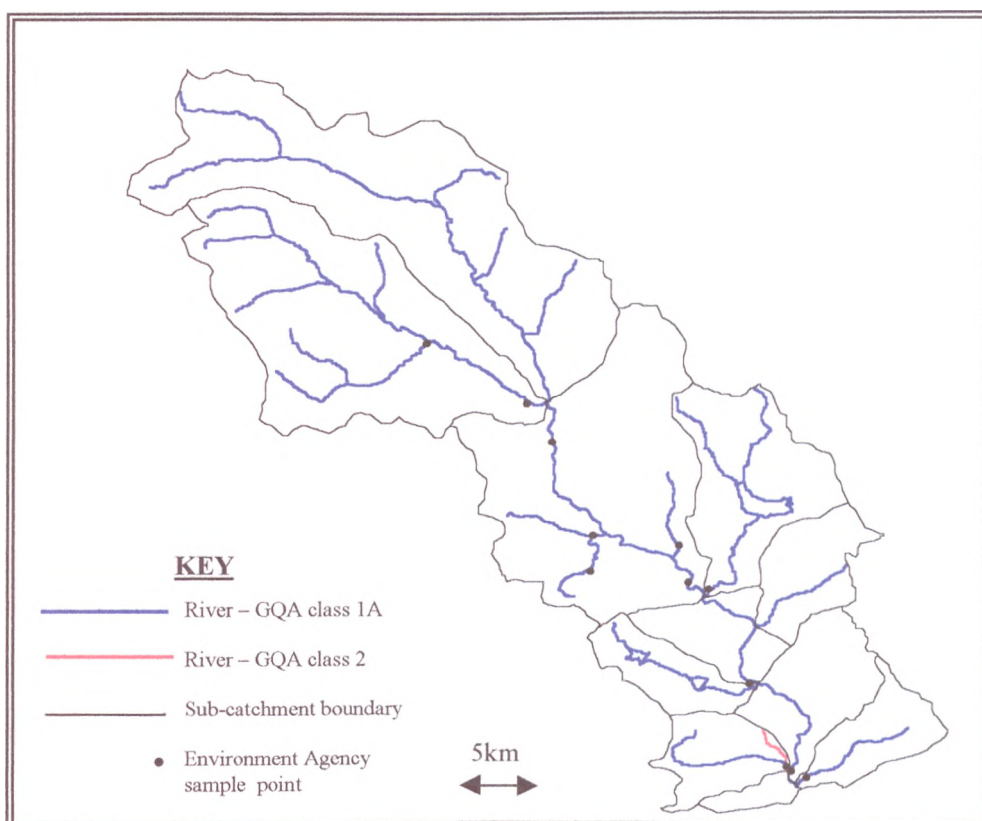
6.3 Initial hazard identification from historical data and catchment audits

As discussed in Chapter 5, historical records of water quality can inform risk assessors of the potential sources of pollution within a catchment area. Historical records may also have a role in the initial scoping of the hazard identification process in order to focus the assessment on those issues of particular importance at an individual intake site. There is a need to identify both discrete pollution incidents and the background fluctuations in water quality that may affect potable abstractions. This section assesses the potential of a number of historical data sources to identify these hazards. The data investigated are from widely available sources to enable the generic application of such approaches to other catchment areas. General river quality assessments are investigated, as are results from routine monitoring carried out at the intake, and pollution incident records.

6.3.1 Water quality history of the upper River Wharfe

The upper reaches of the River Wharfe are monitored at several points by the Environment Agency. Water samples are assessed against the chemical GQA (General Quality Assessment) standards, grading water according to dissolved oxygen levels, biochemical oxygen demand and total ammonia. Within the study area the whole river except one tributary was graded as Class 1A (very good) in the 1995 assessment. The remaining tributary (Hambleton Beck) was categorised as Class 2 - fair (Environment Agency, 1997c). The location of the major Environment Agency sampling points together with the GQA grading of each river reach for 1995 are shown in Figure 6.5. Between 1990 and 1995, much of the river was unclassified, however a few reaches were classified as fair and a number of tributaries were categorised as class C or 3 (poor). Thus a small improvement in the overall quality of the river is evident in the 1995 results. Before 1990, water quality was assessed against the National Water Classification system, the precursor to the GQA system, again ranging from 1A (very good) to 4 (polluted). The majority of the defined river reaches in the Upper Wharfe were classed as 1A, with only Hambleton Beck classed as category 2. No GQA assessment has been carried out since 1995.

Figure 6.5 Environment Agency sample points and 1995 GQA grades in the Upper Wharfe



These data show that the quality of the Upper Wharfe is generally very good, as illustrated by the considerable stretches of Class 1A river. However, GQA data give little indication of either any seasonal fluctuations in water quality or of pollution scenarios that may be experienced in a particular catchment. It is much more suited to broad-scale comparisons of general water quality on regional or national scales. The summary information available from GQA grades is not therefore suitable for identifying pollution hazards in discrete catchment areas. More detailed information is required.

Archived water quality data for individual sample points within the Upper Wharfe is held by the Environment Agency and YWS. These data were investigated to assess whether they have a potential use in the identification of events that may affect potable supply abstractions. To highlight parameters that may present a hazard to such abstractions, the data were compared to standards stipulated in the 1989 Surface Water (Classification) and the 1989 Water Supply (Water Quality) Regulations. These regulations were identified in Chapter 4 as suitable indicators of hazard presence. The DW2 values were used for comparisons to the Surface Water (Classification) Regulations due to the treatment processes in place at the works fed from the Lobwood river intake, as described above (HMSO, 1989a).

Raw water quality data held by the Environment Agency was obtained for four key sites upstream of the Lobwood intake for the period 1991 to 1996. In general most parameters monitored were well below the values stipulated for raw waters to be abstracted for use as potable water. At the downstream site, levels of lead approaching the raw water standards were experienced, indicating a potential pollution hazard. The sources of this contaminant should therefore be investigated and identified. Alkalinity and hardness values found in the river were well in excess of the drinking water standards as would be expected from a limestone catchment. However, as liming and pH correction is involved in the treatment processes, these parameters are considered to be of minimal risk to drinking water quality. Changes in alkalinity or hardness in the catchment may however affect the mobilisation of other elements such as trace metals, consequently affecting treatment costs and efficiencies.

YWS records of water quality during 1995 at the Lobwood intake were compared to the standards stipulated in the water quality regulations in order to give an initial indication of potential problems that may be experienced. Raw water at the intake site is sampled approximately three times a week. Samples are analysed for the eight parameters seen in Figure 6.6 plus Ammonia-N. Levels of Ammonia-N were frequently below the limit of detection during 1995, with only 10 samples having measurable quantities. The maximum level detected during 1995 was 0.05 mg l^{-1} which is well below the 1.5 mg l^{-1} level set in the Surface Water Regulations and 0.5 mg l^{-1} as stipulated by the standards for treated drinking water. Ammonia-N may indicate the presence of other potential pollutants and may therefore warrant further investigation.

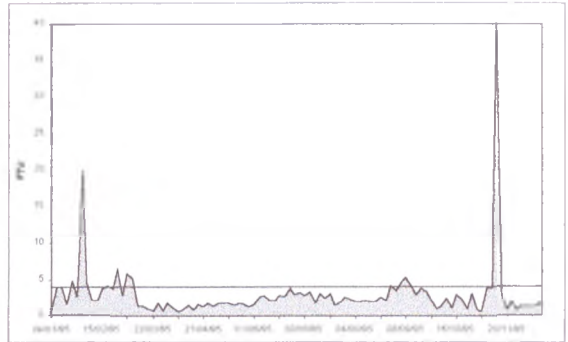
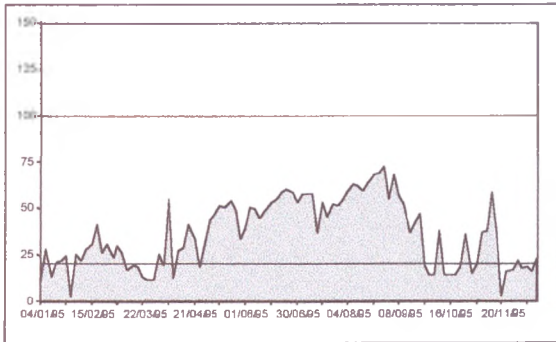
In Figure 6.6, the variation of water quality parameters (shaded grey area) are plotted against the standards set in the surface water regulations (red line) and the drinking water supply regulations (solid black line). Where one of the lines is omitted from the graph no standard is stipulated for that parameter in the related regulations. The standard for pH in drinking water has a minimum of 5.5 and a maximum of 9.5, hence the two lines shown in Figure 6.6 c).

Levels of discoloration seen in the raw intake water during 1995 (Figure 6.6a) were frequently above the 20 Hazen unit standard of the water supply regulations. Although levels did not reach the maximum permissible level for DW2 raw waters of 100 Hazen units, values of more than 50 Hazen were commonly seen during the late summer and autumn months. The discoloration of water could therefore prove a potential problem especially if difficulties were experienced with treatment processes, as levels in the raw supplies are consistently too high for drinking water. Factors promoting the discoloration of water in the catchment (especially during the summer and autumn months) therefore warrant further investigation and should be investigated in any risk assessment of this intake site.

Figure 6.6 Quality of raw water at the Lobwood intake during 1995 compared to the 1989 Water Supply (Water Quality) and 1975 Surface Water (Classification) Regulations

a) Colour (Hazen units)

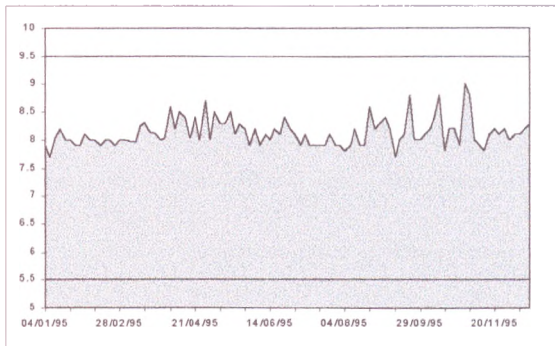
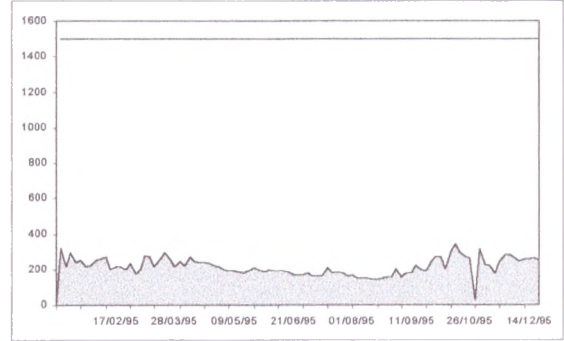
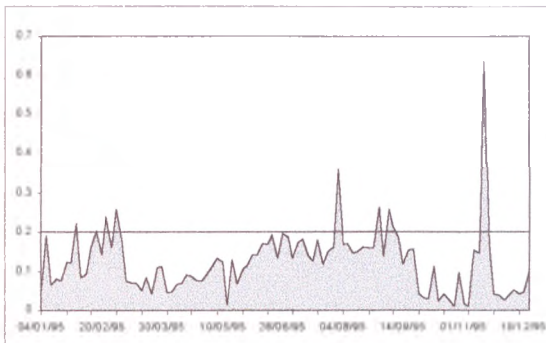
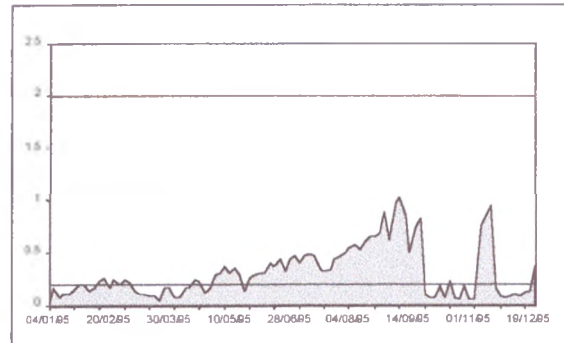
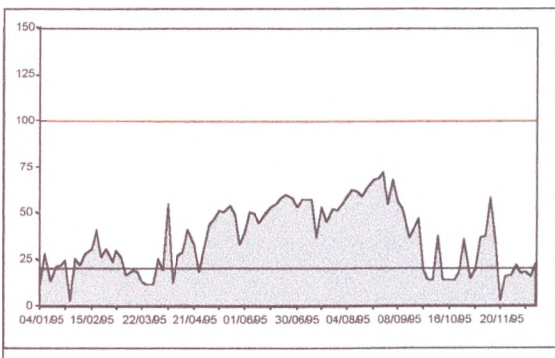
b) Turbidity (FTU)



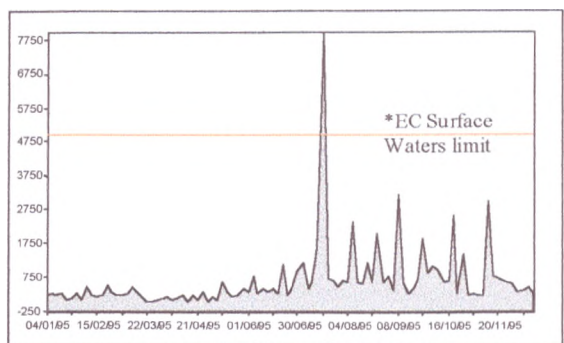
(Source: YWS raw water daily monitoring samples)

Figure 6.6 continued.

c) pH (max 9.5, min 5.5)

d) Conductivity ($\mu\text{S cm}^{-1}$)e) Aluminium (mg l^{-1})f) Iron (mg l^{-1})g) Manganese (mg l^{-1})

h) Total coliforms (per 100ml)



(Source: YWS raw water daily monitoring samples)

Turbidity levels during 1995 were below the 4 FTU (formazin turbidity units) level for drinking water for much of the year, but peaked at higher levels on numerous occasions (Figure 6.6b). One such sample has a turbidity of ten times the acceptable level in drinking water. As with discoloration, the potential therefore exists for turbidity problems in drinking water to be experienced as a result of high levels in raw waters, but with the major potential impacts being on treatment process efficiency and costs.

Turbidity is often considered as an indicator for other potential pollutants as highly turbid water can indicate an increase in overland flow in the catchment (and hence the mobilisation of polluting material).

Hydrogen ion (pH) levels at the intake are well within the drinking water standards (Figure 6.6c). No standards are stipulated for raw waters as the pH is changed to optimise the performance of several stages of the treatment process. Levels of conductivity (Figure 6.6d) are considerably less than the drinking water standards (the annual average must not exceed $1500 \mu\text{S cm}^{-1}$) and do not indicate the presence of a hazard to supply quality.

High levels of Aluminium, Iron and Manganese are seen at the intake site and could potentially affect supplies (Figures 6.6e – g). Aluminium peaked above the 0.2mg l^{-1} level stipulated in the drinking water regulations on several occasions (no standard is set for raw waters). Iron and Manganese also exceeded their respective drinking water standards on several occasions and Manganese peaked above the 0.1mg l^{-1} stipulated for raw waters. Factors causing elevated levels of these metals in river water at this site should therefore be investigated further.

Coliform levels are consistently above the standard for drinking water (0 coliforms per 100ml) and peaked well in excess of the raw water standard (set only in the EC Directive not the resulting UK Regulations) on one occasion (Figure 6.6h). Potential sources of coliform bacteria should also be investigated further.

The variations in riverine concentrations of several parameters over a short period of time discussed above, has indicated some of the potential causes for concern in the catchment. A number of water quality issues have been identified and investigation into their sources recommended in later stages of the hazard identification. Hazard identification from historical records of routine monitoring programmes is however constrained by the limited number of parameters that are routinely monitored at intake sites. More intensive monitoring of known risk parameters following a risk assessment could help reduce this problem.

The following parameters have been identified as potential pollutants requiring further investigation: aluminium, colour, iron, manganese, lead and faecal bacteria (coliforms). The potential impact of overland flow events has also been highlighted. Whilst these indications of 'background' levels of water quality are useful in the identification of several parameters as potential hazards, these data do not inform us of the nature or sources of actual pollution events. In order to address this shortfall, information about discrete pollution incidents was also considered in the scoping of the hazard identification stage.

6.3.2 Pollution incidents in the Upper Wharfe catchment

As discussed in Chapter 2, the reporting of surface water pollution incidents has varied widely in recent years. The Environment Agency currently hold three different databases of pollution incidents for the study area. The first covers the period from the creation of the NRA (mid-1989) to the end of 1993 and the second from the beginning of 1994 to mid-1995. The third database covers the period from the start of 1995 to the present, overlapping the second for a period of several months (Lambert, 1996). Chapter 2 concluded that catchment specific data are required in order to identify pollution hazards to supply intakes. Incident data must therefore be spatially referenced. Early pollution incident records are only available as summary information but these can be queried at the major catchment scale. In the area covered by the North East region of the Environment Agency geo-referenced pollution incident data are only available from the April 1994 and are in two separate formats representing the two reporting periods.

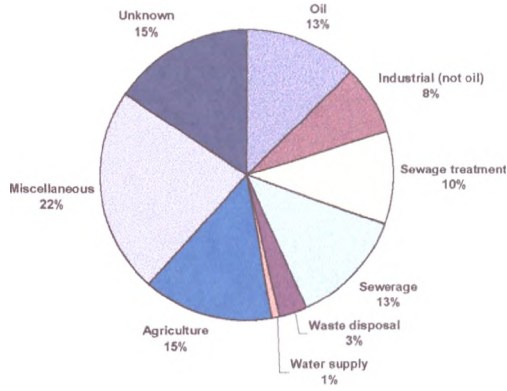
For incidents prior to 1994, only summary data are available, reporting the number of pollution incidents in the catchment area by their source, as shown in Figure 6.7. Whilst this information is limited in detail and covers the whole of the Wharfe catchment, it is of use at this stage for the initial scoping of the hazard identification process as it indicates the major types of pollution present in the catchment. Major / severe incidents are of particular interest as these represent incidents which may result in the closure of potable supply intakes (see Chapter 2 for further definitions).

Figure 6.7 clearly shows the impact of agriculture, and in particular cattle, on water quality in the catchment. Agricultural sources account for some 15% of all incidents, and a large proportion (45%) of all severe incidents between 01/07/89 and 31/12/93 were from cattle related sources. The potential hazard posed by waste water activities is highlighted by the large number of pollution incidents from both sewage treatment and sewerage sources. The significant proportion of incidents classed as 'other' or 'miscellaneous' (37% of all incidents and 22% of severe ones) indicates an inherent weakness in the summary data. Some 158 incidents remain unclassified, providing no indication of their possible sources or impacts on water quality.

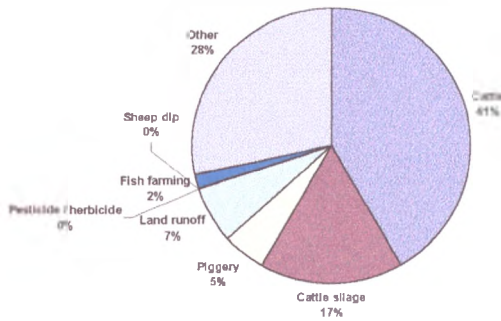
No consideration is given to non-point sources unless a direct impact on the river has been caused. These data only refer to pollution incidents for which a source has been identified and do not consider the contribution of contaminated runoff known to cause problems in upland areas (Mitchell, 1991).

**Figure 6.7 Surface water pollution incidents in the River Wharfe by source
(01/07/89 to 31/12/93)**

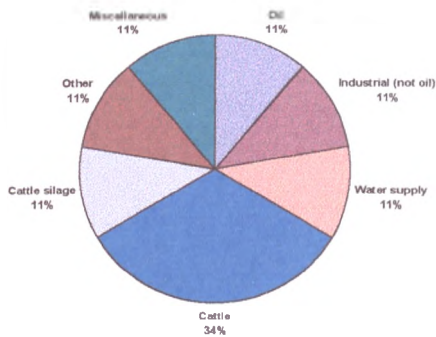
a) All incidents (total 412)



b) Agricultural incidents (60)



c) Severe incidents (9)



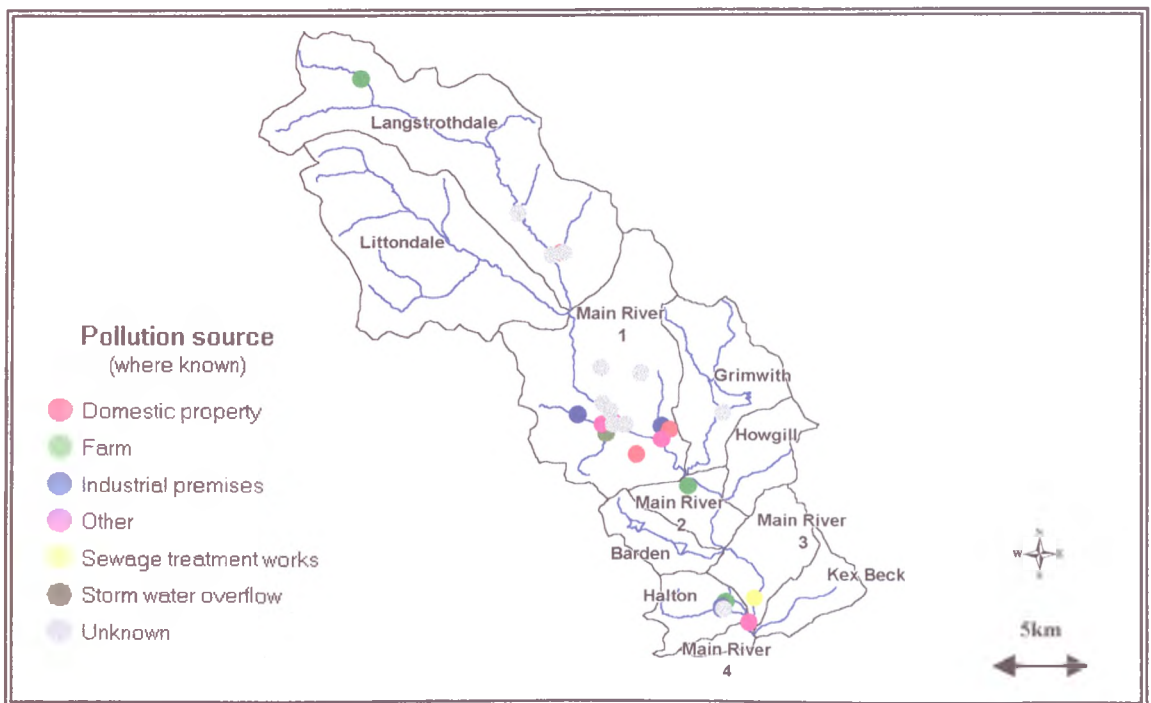
(Source: Lambert – *Pers Comm*)

Consideration of these summary data therefore suggests a number of potential hazards in the Wharfe catchment, primarily cattle farming and silage making, waste water collection and treatment, and oil spillage / contamination (13% of incidents). However, these data give no indication of the precise geographical location of the primary hazard source areas.

Since April 1994 pollution incident reports have included national grid references enabling their spatial distribution to be investigated. This was done by importing the data in the MapInfo GIS. Pollution incident data were originally obtained from the Environment Agency as hard copy printouts. Those incidents with a grid reference within the catchment boundary were then inputted to a Microsoft Excel spreadsheet where the grid references were converted for use in the national co-ordinate system. Using MapInfo, point features were created from the co-ordinate columns and mapped. Attribute information describing the incident date, location, watercourse affected, category, cause and precise sources were stored in the associated MapInfo table.

MapInfo was used for this because of its capacity to read data directly from an Excel spreadsheet and create point features from the columns of X and Y co-ordinates automatically. The display of these features in WINGS would involve the creation and editing of several text files, the manual creation of point features and attribute designation. Using this approach the data layer can be transferred between the software automatically using MIFMERGE - a program that converts MapInfo import/export files (*.MIF) to WINGS import files (*.IMP) for use in WINGS. The location of pollution incidents occurring in the Upper Wharfe catchment during 1994 and 1995 is shown in Figure 6.8.

Figure 6.8 Pollution incidents in the Upper Wharfe 1994 – 1995
(by source)



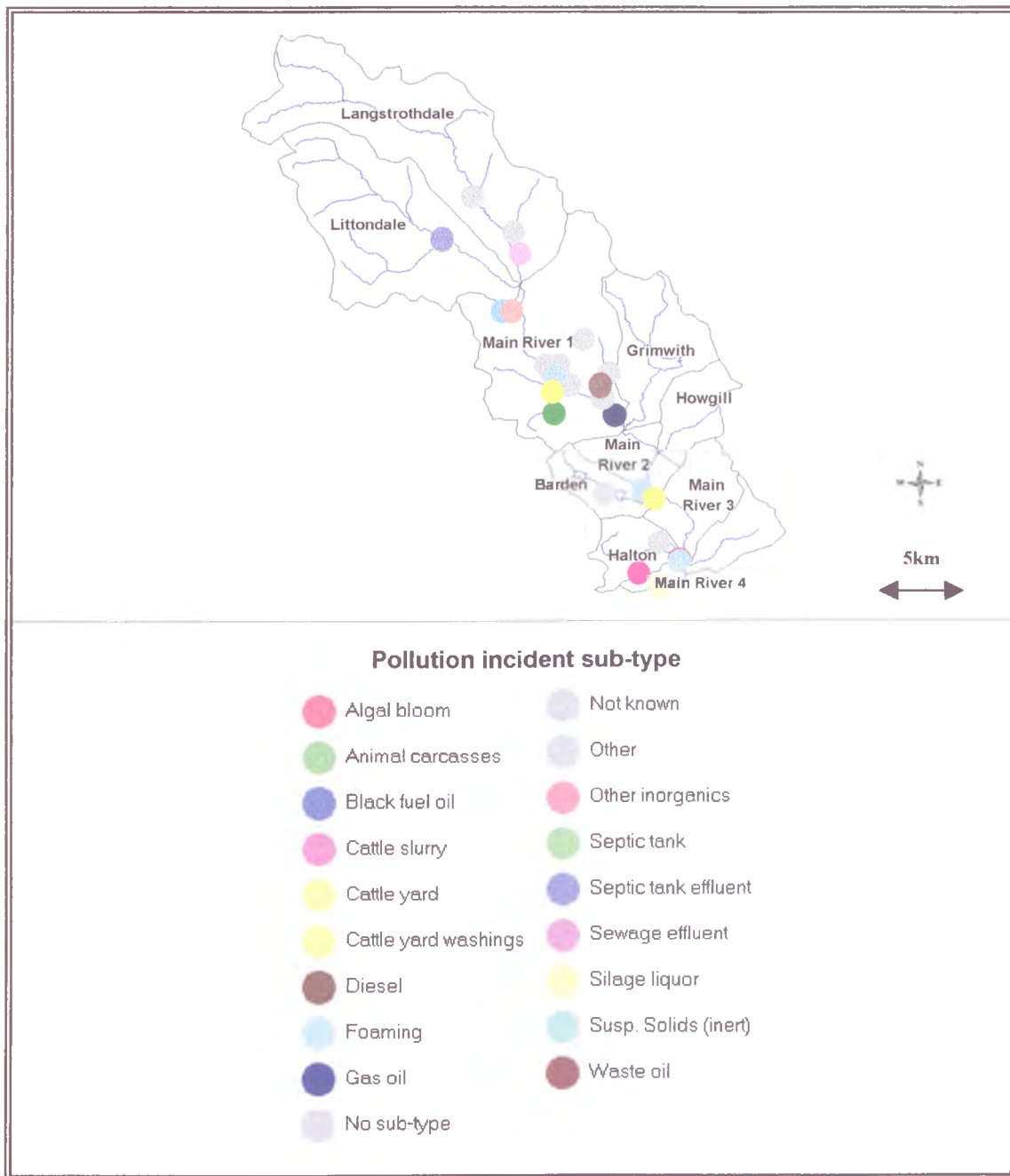
(Source: Lambert – Pers Comm)

A significant number of these incidents were from sources in or near domestic properties. The majority of these were located around Grassington, the largest village in the study area. Contamination from domestic properties also occurred in the headwater villages of Kettlewell and Starbotton, as well as in less populated areas adjacent to tributary streams. Pollution from industrial premises occurred in three of the tributary streams, two of which were oil related and the third unclassified. The premises associated with these spills are not named in the incident records available and the location given is the site of the reported pollution, not the exact source.

In accordance with the information gained from the summary data (for 1989-1993) the main pollution problems are sewage, cattle sources on farms and oil spills. Interestingly there was one incident of natural river turbidity (noted in the previous discussion of general water quality), that was considered severe enough to be reported as a pollution incident.

Pollution incident data from the third database (1st January 1995 to 30th July 1997) no longer contains reference to the precise source of the incident, but does group incidents by sub-types (Figure 6.9). These sub-types again illustrate the variety of pollution sources in the catchment and give some indication of the location of pollution hazards.

**Figure 6.9 Pollution incidents in the Upper Wharfe 1995 - 1997
(by sub-type)**



(Source: Lambert – Pers Comm)

The impact of agricultural sources such as cattle slurry, yard washings and silage liquor is once again evident from these data. The main other pollution types are oils and sewage / sewerage sources. The sub-type of a large number of the incidents were not identified, giving no indication of the contaminating material, the severity of pollution or their possible sources.

Pollution incidents in the Upper Wharfe appear to be concentrated in the Main River 1 sub-catchment area. This is likely to be because Grassington village, the largest in the study area, is within this sub-catchment. The potential for pollution incidents to be reported by residents and visitors is therefore much greater in this more densely populated area.

The reliance of previous studies (such as that by Cole *et al.*, 1988) on historical data was criticised in previous chapters as historical records only identify known hazards. In the Upper Wharfe the additional problem of data reliability has meant that information describing previous pollution scenarios is limited to a little over two years. Prior to this period pollution sources were largely unknown or poorly reported in the summarised data and inferences from routine water quality monitoring are the only indicator of the spatial distribution of water quality problems.

Pollution incident data available from the Environment Agency give no indication of non-point sources, nor of potential hazards that have not been witnessed as actual incidents in a watercourse. The use of pollution incident data as they currently exist is therefore limited to highlighting a selection of potential types and locations of pollution seen historically. In addition, the grid reference location shows where the pollution was reported in the river and does not identify the actual source which may be some distance upstream. Pollution incident data are not therefore suitable for identifying all areas of *potential* hazard to water quality.

6.3.3 Catchment auditing exercises

In the initial stages of the project several visits were made to the catchment area, during which physical inspections of the land were carried out in order to identify potential sources of water pollution. As was evident from the historical data, the primary pollution hazards are posed by agricultural activities due to the dominance of this land cover type in the catchment. The following hazards were also noted in the catchment area:

- Fish farming
- Caravan parks
- Road network
- Parking areas
- Quarrying
- Forestry
- Urban areas

The villages in the study area were investigated in turn and the location of any sites considered to pose a potential pollution hazard (e.g. petrol stations) were noted. These point sources are used in later hazard mapping exercises (see Chapter 7). In addition, the catchment area was searched using the Electronic Yellow Pages (available via the Internet). No industrial sites were found apart from Swinden quarry. Interrogation of the public listing of Integrated Pollution Control (IPC) registered

sites listed only the quarry in the study area (again accessible via the Internet). No reported releases to water have occurred at this site to date.

The search for industrial premises was particularly easy in this catchment due its rural nature. If a more urbanised catchment were to be assessed, the use of postcode address files combined with the relevant postcode sectors would identify all industrial and commercial premises within a catchment boundary.

6.4 Summary

Historical records have been used to give an initial indication of potential pollution scenarios in the Upper Wharfe catchment. Records of water quality for the river reaches, obtained from the Environment Agency can be compared to parameters stipulated in the Environment Agency's classification system and for drinking water. No information about possible pollution threats can be gleaned from the general classifications assigned by the Environment Agency as these indicate the overall condition of the river water. More detailed investigation of historical records is therefore required. The best approach to the initial scoping of hazard identification was found to be the comparison of historical quality records with standards set in the various water quality regulations introduced in previous chapters. However, this is constrained by the limited number of parameters that are routinely monitored at intake sites. More intensive monitoring of known risk parameters following a successful risk assessment exercise could help reduce this problem.

Early pollution incident records are only available as summary information but can be queried at the catchment scale, therefore providing some indication of the pollution history of a river catchment. Grid-referenced data are available for incidents since July 1994 and the reporting format was only standardised in 1995. This has limited the analysis of geo-referenced data to a period of just over two years. This information can be used to give an indication of the types of pollutants recently experienced in the catchment and help define the scope of hazard identification activities. Pollution incident data also have the potential to provide information about hazard probability. This is investigated further in Chapter 9.

Chapter 2 identified a number of drinking water pollutants that are of national and regional significance, namely pesticides, faecal bacteria, *cryptosporidia*, manganese, polycyclic aromatic hydrocarbons (PAHs) and trihalomethanes (THMs). In addition, the study of catchment-specific historical data in this section has identified several additional parameters for concern (discoloration, lead, aluminium, iron, manganese and pollution incidents from agricultural, oil and sewage sources).

Together with the catchment auditing exercises briefly described above, this has led to the following list of potential pollution hazards in the Upper Wharfe catchment (Table 6.2).

Table 6.2 Potential pollution hazards & parameters for concern

Agricultural	
Animal pens - faecal material	Cryptosporidium spp.
Storage of agricultural chemicals	Crop spraying (pesticides & fertilisers)
Sheep-dips (phenolics & pesticides)	Silage stores (phenolics)
Surface runoff from fields (pesticides & fertilisers)	Yard washing (bacteria, cryptosporidium, pesticides)
Milk spillage	
Industrial	
Illegal discharges	Consented discharges
Land-fill leachates	Chemical stores (fire damage, leaks etc)
General	
Road traffic accidents	Storm drains / combined sewer overflows
Leachate from soak-aways	STW discharges
Surface runoff from roads	Illegal dumping of wastes (chemical drums, animal carcasses etc.)
Drainage from mines	Drainage from storm sewers & drains
Caravan / Camping sites	Car parks
Water discoloration	Aluminium
Manganese	pH
Iron	Lead
Mine spoil	Natural sediment / erosion of floodplain areas
Precipitation inputs	

The approach of previous studies (such as that by Cole *et al.*, 1988) which relied heavily on the use of historical data has proved to be unsuitable for the Upper Wharfe, with historical records only supplying sufficient information for pollution hazards to be theorised or at best summarised. As with all predictions based on historical data, only pollution hazards that have been previously witnessed can be identified. Historical information is of some use in clarifying the scope of a pollution risk assessment, and identifies those parameters that should definitely be included in any assessment. However, this approach fails to identify the actual sources of hazards or give sufficient flexibility to identify as many potential pollution hazards as possible. The need for more detailed hazard identification techniques has therefore been clearly illustrated.

There is therefore a need to widen the scope of the hazard identification process beyond the study of historical records to avoid the failings of past studies caused by incomplete data. In order to identify as many of the potential pollution hazards as possible the following chapter considers the actual physical characteristics of the catchment area. For reasons of practicality, these are broadly based around the types of contamination seen in the historical records studied above, and problems experienced in similar upland catchments.

Chapter 7

Hazard identification in the Upper Wharfe catchment (2): using digital data & mapping

7.1 Introduction

This chapter describes the GIS-based approaches used in the identification of various point and non-point source pollution hazards in the Upper Wharfe catchment area. Particular emphasis is placed on the creation of Source Trees (introduced in Chapter 5) and using digital data within a GIS environment to automate the hazard identification process. GIS based hazard mapping has not been conducted for water quality parameters previously, but is potentially a very powerful tool. Throughout the chapter, the GIS techniques used are described to demonstrate the potential of GIS-based hazard identification.

Two geographic information systems have been used in this study, MapInfo Professional™ (Version 4.0) and WINGS™ (Version 2.4.1). Both systems operate under Microsoft Windows and were used with the Windows 95 operating system on a desktop Pentium PC. Whilst WINGS is an established package in use within YWS, its fundamental capabilities are only just being expanded beyond digital mapping and basic spatial querying. MapInfo provides more advanced spatial analysis tools and is therefore expected to have greater potential for the creation and analysis of catchment hazard maps.

There is little evidence of GIS-based water quality hazard mapping of this variety in the literature (see only Breach *et al*, 1994, Smith *et al*, 1996, Foster *et al*, 1997 and Foster & McDonald, 1998). However, this represents a significant potential application of environmental digital data. The digital data used in the hazard identification stages were obtained from the Yorkshire Water GISLAB initiative described in Chapter 3. These include data describing river networks and catchments, land cover, agricultural census data, topography, road networks, soil data, point features describing discharges and camping sites, and OS vector and raster maps of various scales. Additional digital files were created within the GIS packages from machine readable and hard copy information supplied by various organisations including the Environment Agency and Edinburgh Data Library. A comprehensive list of the data, their coverage, resolution (scale), licensing agreements, data types and associated attributes is given in Appendix A. These data are used to create hazard maps from the source trees developed for each water quality parameter.

The performance of YWS' GISLAB application (built on a WINGS GIS platform) and MapInfo GIS are compared in section 7.3 and conclusions drawn as to the suitability of their use for catchment scale hazard identification.

In the concluding section, the potential of GIS software and techniques for hazard identification are discussed and the characteristics of the hazard maps created for the Upper Wharfe catchment summarised.

7.2 Source Trees & GIS-based hazard mapping

The previous chapter identified numerous parameters of concern to water supply abstractions from the Upper Wharfe catchment. In addition to the previous approaches, GIS-based hazard identification can be used to identify specific areas that may be the source of known problems, and also identify other potential hazards from a knowledge-base of problems experienced in other upland catchments. For example, whilst neither cryptosporidium nor phenolic compounds have been routinely detected this far upstream in the River Wharfe, contamination is known to exist in similar upland areas of Yorkshire (see for example, Mitchell, 1992, Foster & McDonald, 1996 and Marshall, 1997). The catchment characteristics likely to cause such contamination can therefore be used to identify source areas for parameters about which no historical data are available. This represents a considerable advantage over the use of historical data, (the approach used by previous authors) and addresses one of the major weaknesses of such approaches as identified in Chapter 4. The hazard identification stage could therefore be extended to consider all 56 parameters of the 1989 Water Supply (Water Quality) Regulations. However, in this case, the parameters considered are limited by the types of digital data available at reasonable cost. In addition, limiting the assessment to key parameters to demonstrate the methodology will also enable verification fieldwork to be carried out.

The parameters being considered in this chapter represent a combination of the contaminants identified in Chapter 6 and those experienced in other upland catchments. These are: *cryptosporidium; pesticides; oils & greases; colour; trace metals; faecal bacteria; lead; nutrients; and phenolic compounds.*

Source trees are used to relate the characteristics of the sub-catchment areas to potential water quality hazards. In this way the areas of land that are of particular concern can be identified and mapped using the GIS. This potentially allows risk mitigation strategies to be targeted at the key areas (see later chapters). The source trees form the basis of the GIS data models, identifying the necessary data layers and how they are combined. Where generic, published values (such as infection or application rates) exist these are used to help quantify the relative importance of contributory factors and hence sources areas. GIS overlay and map algebra techniques are used to combine these data to produce the hazard maps. The aim of this approach is not to quantify exact amounts reaching the river or model flows to the intake site, but to look at the relative contribution of potential source areas in terms of their level of hazard.

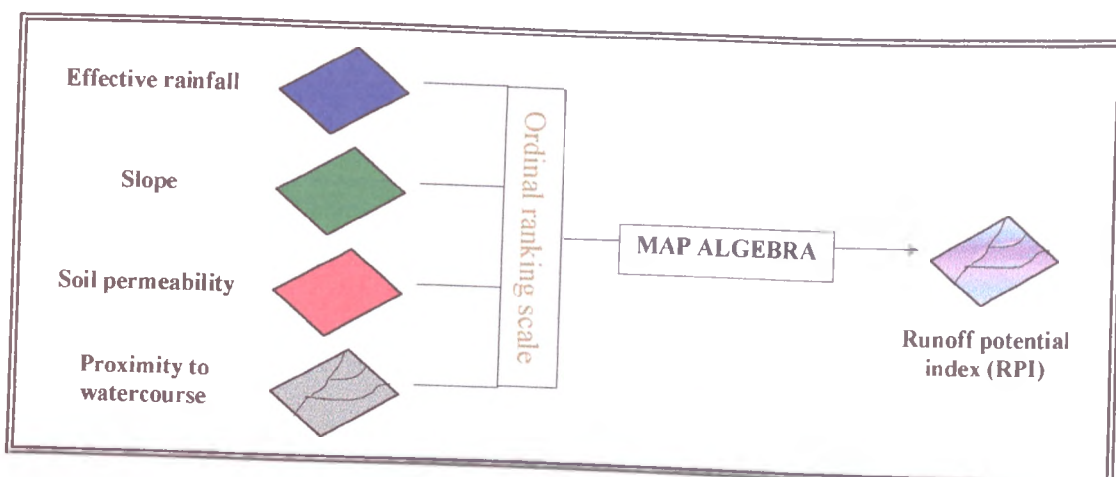
7.2.1 Runoff Potential Index

A key factor governing the impact of diffuse pollution hazards present on the land surface is the hydrological response of a catchment area. The nature of water movement around the catchment will determine the quality of the surface and groundwater, and subsequent abstractions downstream. A number of hydrological processes operate in a river catchment. These include runoff across the land surface (overland flow), seepage into the soil layers and to groundwater (infiltration) and lateral movement through the ground (throughflow) (Dunne & Leopold, 1978; Kirkby, 1978). These processes vary both spatially and temporally within catchment areas.

Although the catchment is in a limestone area as discussed in the previous chapter, the process likely to have greatest impact on hazards located on the land surface is overland flow (surface runoff) as this may quickly transport pollutants directly from the land to a watercourse. These contributing areas supply water directly to the stream much quicker than infiltration and throughflow processes. It is therefore important to determine the expected spatial variation in surface runoff in order to assess the relative significance of any hazards present on the catchment surface. Hazards located on or near these areas will therefore have greater potential to cause an impact on the downstream water quality, and consequently the supply intake.

Surface runoff is influenced by a number of parameters, the most important of which are the slope of an area and the permeability of the land surface. Precipitation is the driving force behind catchment hydrology and must also be taken into consideration when determining the potential for runoff to occur. The impact of a potential pollutant will also be influenced by the distance it is transported before reaching a watercourse. A runoff potential index (RPI) has therefore been developed based on four geographic variables determined from the digital data, namely effective rainfall, soil permeability, average slope and proximity to a watercourse, as shown in the diagram below (Figure 7.1).

Figure 7.1 Components of the Runoff Potential Index (RPI)



The runoff potential index (RPI) of an area of land is defined on an ordinal ranking scale of five points, as follows:

<i>RPI ranking of:</i>	1 = <i>very low runoff potential / no data</i>
	2 = <i>low runoff potential</i>
	3 = <i>moderate runoff potential</i>
	4 = <i>high runoff potential</i>
	5 = <i>very high runoff potential</i>

The effective annual rainfall data were ranked into five categories, as were average slope¹, and proximity to a watercourse and then combined using MapInfo. The soil permeability ranking was based on the description given in the Hydrology of Soil Type (HOST) classification as defined by Boorman, Hollis & Lilly (1991) and was again represented on a five point scale. The rationale of the ranking of HOST classes was that soils described as having freely drained surface layers, high permeability and moderate to high subsurface storage capacities were ranked 1 (very low) for surface runoff. Water-logged or permanently wet soils with negligible subsurface storage capacities were ranked 5 (very high) for surface runoff potential. The full range of ranks and descriptions of soil HOST codes is given in Appendix B.

The ranking boundary values used in the creation of the RPI are shown in Table 7.1 below. Five equal ranges of rainfall data were selected from those seen in Wharfedale. This was based on the 1941-1970 long term average and whilst not ideal, it represents the most recent data available in digital format. For the slope values, the boundaries of the lower rankings were derived from literature on catchment characteristics and water quality (Boon *et al.*, 1988; Mitchell & McDonald, 1995) with the remaining classes forming roughly equal category sizes up to 32°, beyond which the slope is considered to be the dominant factor. A watercourse is as defined by the 1:50,000 Institute of Hydrology digital data. Proximity ranks were determined by creating buffers around the rivers data. MapInfo can then select cells within these buffer regions (based on the position of the cell centroid).

Table 7.1 Rank classification boundary values for components of the RPI

	Rank 1 (Very low)	Rank 2 (Low)	Rank 3 (Moderate)	Rank 4 (High)	Rank 5 (Very high)
Effective rainfall (mm yr ⁻¹)	424 – 618	619 – 813	814 – 1008	1009 – 1204	1205 – 1399
Slope (degrees)	>= 0 and < 8	>=8 and <16	>= 16 and <24	>= 24 and <32	>= 32
HOST data (HOST classes)	1, 2, 3, 5	4, 16, 17, 19	6, 7, 8, 13, 22,	10, 14, 18, 20, 21, 23, 24	9, 12, 15, 25, 26, 27, 29
Proximity to watercourse (m)	1500 – 5000	500 – 1500	100 – 500	11- 100	0 – 10

¹ Average slope was determined by creating a Triangular Irregular Network (TIN) surface from the 1:50,000 OS contour data using ARC/INFO.

The individual ranks for each area of land were then summed to give an overall ranking of runoff potential (RPI) of between 4 and 20. These are calculated for the smallest spatial unit of the datasets used, the slope TIN, in order to minimise the spatial approximations. Some approximations were unavoidable as data of various resolutions were being combined so coarser scale data are subdivided by those of finer resolution. An example of the spatial variability in RPI values in part of Upper Wharfedale can be seen in Figure 7.2. The RPI ranking developed here is specific to the Upper Wharfe catchment as the rainfall ranks are based on local maxima and minima. For the RPI to be truly generic, data would be required for the whole region and/or country, depending on the area of application.

Figure 7.2 Runoff Potential Index (RPI) for part of the Upper Wharfe catchment



From Figure 7.2 the impact of local slope angle on runoff potential can be seen in the tributary valleys, where the high RPI values show the steep valley sides. Closer to the main river channel, shallow-sloping floodplain areas highlight the influence of soil type on the potential for runoff. In these areas the larger scale (100m) soil data dominate the map, highlighting one of the initial problems found when using data of varying scales from a number of sources. However, even within these areas, the importance of slope, rainfall and proximity on the RPI values is shown by the red flecked areas within the grey 'blocks'.

The RPI is similar in principle to the approach taken in the development of the Farm Animal Pollution Risk Management System (FARMS). FARMS, developed by WRc, provides a national view of pollution potential from livestock farming (Woodrow, 1993). However, FARMS was intended only to give a national ranking of large scale catchments so that further investigations could be carried out on the ground.

The data used in the study were coarse in spatial resolution due to the large volumes of computer storage space required for a national dataset. The FARMS project did not consider risks other than the impacts of slurry spreading in rural catchments (Oakes, 1996 - *Pers Comm.*) and did not take into account proximity to a watercourse as a variable when estimating the runoff potential of a particular area of land.

The RPI is fundamental to the hazard mapping carried out in the following sections, highlighting those areas of land from which hazards are most likely to reach the watercourse.

7.2.2 *Cryptosporidium*

Introduction and background

Cryptosporidium parvum is a protozoan parasite that can cause self-limiting diarrhoea in human and animal populations. Cattle and sheep are particularly susceptible to infection and can excrete large numbers ($>10^{10}$ animal⁻¹ day⁻¹) of cryptosporidial oocysts onto catchment areas (Kay & McDonald, 1991). The oocysts are environmentally robust, spore-like forms 4-6µm in diameter that may readily enter raw water supplies from catchments but are extremely difficult to remove by conventional drinking water treatment. Children and elderly people are most affected by the resultant disease, cryptosporidiosis, and fatalities may occur in immuno-suppressed populations. This disease is believed to have an effective dose as low as ten oocysts (Smith, 1992).

Cryptosporidium therefore represents a diffuse source of pollution that is a major potential hazard to public health through the contamination of water supplies obtained from British upland catchments, primarily due to the large numbers of cattle and sheep grazing in these areas. Seager *et al* (1992) describe the identification of areas at high risk from farm wastes pollution by combining animal stocking densities, climate, soil type and catchment topography. A similar approach is taken here.

No enumeration of protozoan oocysts is required by the 1989 Water Supply (Water Quality) Regulations, but as they are more resistant to contemporary treatment processes, the absence of other faecal bacteria cannot be relied upon to indicate their absence.

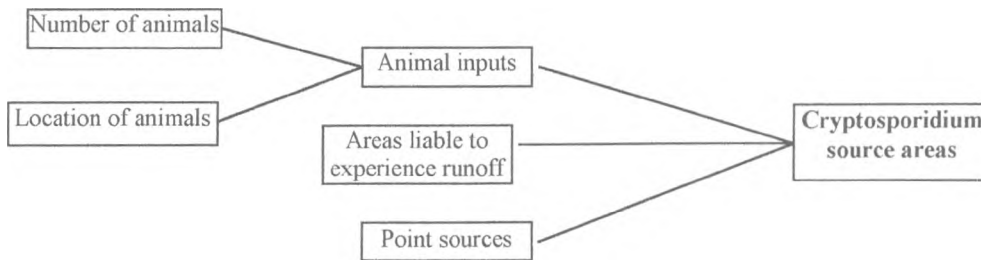
Present knowledge of potential source areas

Cryptosporidium oocysts are deposited on the ground in animal faeces and subsequently washed off the land surface by overland flow events. At the time of writing, concerns about cryptosporidium contamination of groundwater is increasing following an outbreak of cryptosporidiosis in the UK believed to be linked to borehole water. In this study however, transport by overland flow is assumed to be the major input mechanism for cryptosporidium oocysts contaminating surface waters, with throughflow and groundwater inputs of cryptosporidium being minimal. This has been illustrated by other work in the Wharfe catchment (Marshall, 1996).

Building of Source Tree & GIS data model

The production of a Source Tree has two roles. Firstly, to facilitate the GIS-based modelling of pollution hazard and secondly to ensure that as many possible hazard sources are considered. The creation of source trees for *Cryptosporidium* considers all possible sources of the known causal activity – the production of animal faecal waste. Both point and non-point sources of these inputs may exist within a catchment as shown in the Source Tree in Figure 7.3a).

Figure 7.3 a) *Cryptosporidium* Source Tree

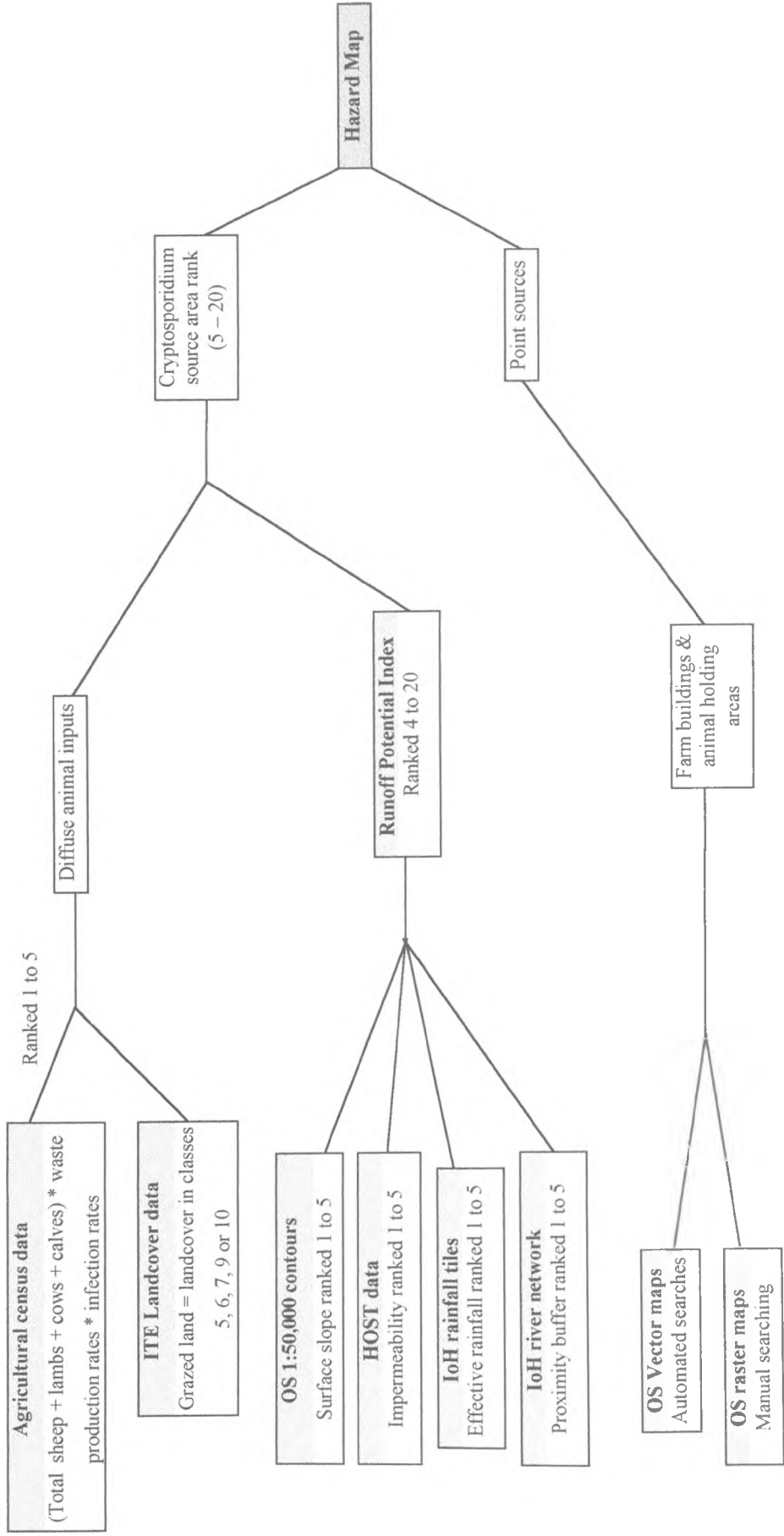


GIS-based modelling of cryptosporidium source areas has not been attempted previously. In this case it is carried out through the combination of several spatial data sets as illustrated by the data model in Figure 7.3b). The most recent Agricultural Census data available digitally for the study area (1995) were taken and the number and type of farm animals in each 2km by 2km grid square extracted from these. All grid squares partly or wholly within the catchment boundary were selected. Stocking densities were then weighted in terms of the faecal production rates of the animal species and estimated average cryptosporidium infection rates.

The location of the animal grazing and holding areas were then obtained at a finer resolution by combining the agricultural census data with the ITE land Cover data. At a resolution of 25m these data allow the sub-division of the 2km grids into smaller spatial units – i.e. narrowing down where exactly in the 4 sq. km the animals are likely to be located. Areas of land that are, or may be grazed were identified as those falling into either of the five following land cover classes: grass heath (ITE class 5); improved grassland (ITE class 6); intensively managed grassland (ITE class 7); moorland grass (ITE class 9) and open shrub moor (ITE class 10). Areas of grazed land identified from these were then assigned the cryptosporidium loading ranks from the agricultural census grid square they fell within. This assumes that all the animals counted in the census graze on areas of land suitable for grazing and not other land cover types (e.g. tilled land).

This produced a data map of the potential oocyst loading for each 25m grid square of the catchment area. The loading was then geographically combined with the RPI developed earlier to show areas where oocysts are most likely to be transported overland to a nearby watercourse.

Figure 7.3 b) Cryptosporidium GIS data model



This was done by selecting all the RPI ranked TINs that fell within the geographical confines of each 25m 'grazed land' grid square and assigning to that TIN the previously determined cryptosporidium hazard rank. The resultant hazard map therefore represents the cryptosporidium hazard potential of each TIN within the catchment area. The map is displayed as a ranking on a five point scale in accordance with the standard protocol of the research (five equal range divisions ranging from very high to very low/negligible hazard).

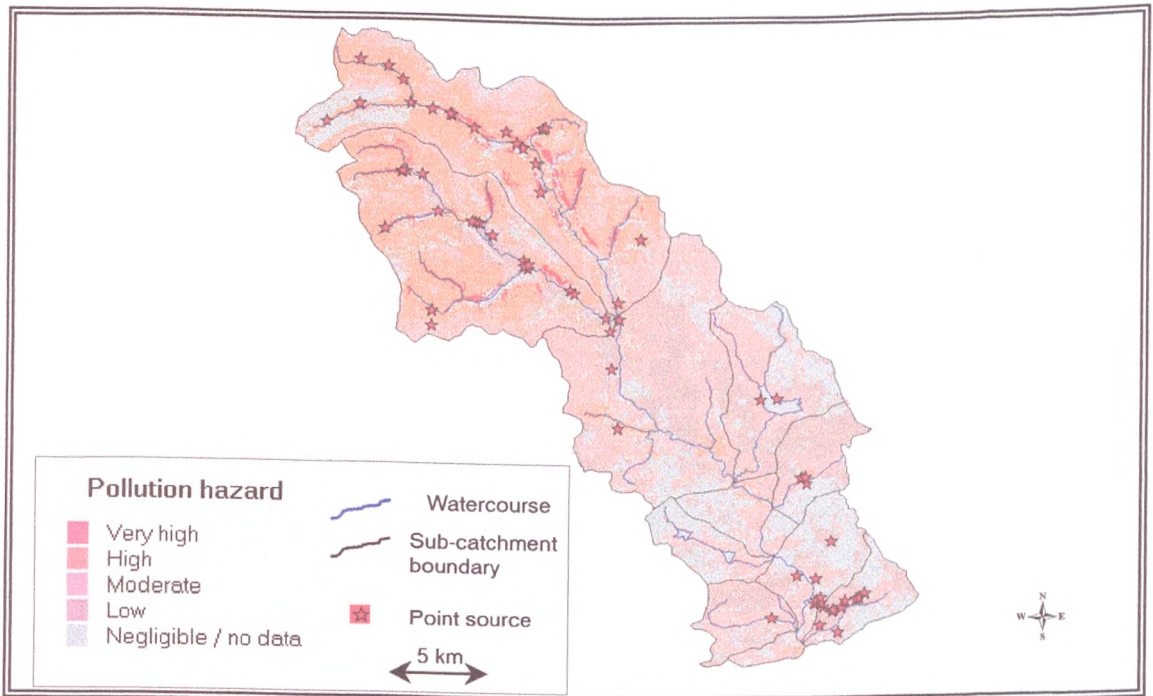
In addition to non-point sources (i.e. faecal deposition), potential point sources were identified from the OS vector maps. Locations such as stock holding areas, farm yards and buildings were selected from the maps using one of two techniques. For much of the catchment data could be obtained using the automated techniques described below. The remainder were identified from visual inspection of the 1:10,000 OS map layer held in GISLAB

Whilst total coverage of the study area with OS Landline maps was prohibitively expensive (as these data were not complete in GISLAB), some automated searching of these data enabled the work load involved in locating of point sources to be greatly reduced. As the maps are stored within WINGS as vector data structures, the textual components of the map are searchable. Thus specific text strings can be searched for using the functionality of the WINGS GIS. This removed the need for extensive visual searches of the catchment areas, and was done within WINGS due to the unique way in which the data were stored within GISLAB. It would be possible to carry this out in MapInfo, but would require the vector maps to be re-imported separately. Only the resultant data files of the point sources were therefore exported to MapInfo. Such techniques are excellent for re-assessment as they only require updated map layers to be purchased and the routines repeated using the newer data, thus removing the need for labour intensive re-examination of paper or raster map layers.

Where the Landline data was not available manual on-screen searches of the 1:10,000 raster background maps were carried out in order to identify potential point source pollution hazards. Points were created on the map at the identified sites and a digital file of the locations and attributes stored in the GIS.

Due to the predominance of overland flow activities in the transport of these oocysts to the watercourses, these point sources areas were also geographically overlain on the RPI map created previously. The combination of the non-point and point source maps therefore showed where all potential source areas coincided with areas liable to transport oocysts into the watercourse, hence identifying the relative hazard of the catchment land areas. The resultant cryptosporidium hazard map for the Upper Wharfe catchment is shown in Figure 7.4. This approach does not identify the number of oocysts transported to the watercourse as this will be dependant upon a number of contributing factors including transport mechanism and is beyond the scope of hazard identification. It does however, illustrate the relative contribution to contamination that different parts of the catchment may make, therefore identifying the hazard to water quality.

Figure 7.4. Cryptosporidium hazard map for the Upper Wharfe catchment



The above hazard map clearly shows the impact of pastoral agriculture on cryptosporidium hazard potential. The upper reaches of the catchment area show much higher hazard rank due to the large number of animals grazing on steep slopes close to the smaller tributary streams. These also represent the area with highest rainfall and the poor draining soils. The Kex Beck sub-catchment in the south east of the study area also represents a significant cryptosporidium hazard due to the large number of potential point sources (farms and animal holding areas) in this area (see Figure 6.3 for key to sub-catchment names).

A cryptosporidium hazard map such as this has immense potential for assisting in the targeted reduction of risk in the catchment. If cryptosporidium problems are experienced in the raw water, then a map such as this can be used to identify the areas most likely to be the source and hence prioritise the location of any remedial actions. The small pixel size of the map enables the hazard rank of individual fields or farms to be compared to neighbouring land areas. Thus the avoidance of grazing in certain fields or sub-catchment areas (of greatest hazard for oocyst transport) during periods of high rainfall is an example of a potential management scenario that could be identified with data at this scale. Further discussion of the potential risk management strategies highlighted by the maps are discussed in later chapters.

7.2.3 Pesticides

Introduction and background

Pesticides represent a significant problem for water supply companies due to the very low concentrations that represent a failure of the Water Supply (Water Quality) Regulations 1989. Fielding & Packham (1990) identify drinking water as the primary source of potential pesticide exposure for many humans. Pesticide compounds are classed as either insecticides, herbicides, or fungicides and are used to kill specific pests or a broad range of species (Gray, 1994). The 1993 UK Pesticide Usage Survey lists 498 pesticide compounds in use in the UK and the number of different types and quantities of pesticides applied to agricultural land are continuously increasing. In humans, pesticides can cause rapid poisoning, with acute effects including nausea, giddiness and restricted breathing. More commonly they cause short-term irritations to the skin, eyes or gastric tract. Older more persistent compounds (such as organochlorines) have been shown to cause cancer, tumours, birth defects and immune system damage following long term exposure (Gray, 1994). Organophosphorous compounds also combat their hosts by attacking the nervous system but are rapidly broken down in the environment and are hence rare in surface or drinking waters. Little is known as to the potential long term effects of the newer pesticides at levels currently considered safe in drinking water supplies.

The regulatory standard specified in the Water Supply (Water Quality) Regulations for total pesticides is $0.5\mu\text{g l}^{-1}$, with the maximum permissible concentration being $0.1\mu\text{g l}^{-1}$ for any individual pesticide. At a level of one part in ten billion this is an effective standard of zero (Skinner *et al.*, 1997), but much criticism has been levelled at these regulations as they take no account of differences in toxicity of the individual compounds. They do however represent one of the more stringent drinking water quality standards. With such minute concentrations required to breach the water supply regulations, the elimination of these compounds from source waters will greatly reduce the need for extensive treatment and reduce the chances of compliance failure. The standards may be amended with the changing regulations highlighted in Chapter 2, but as yet no new limits have been stipulated. Pesticide contamination also produces adverse organoleptic effects (taste and odour problems) but as these are at higher concentrations than the public health limits these are rarely considered a problem.

A recent study by the Environment Agency investigated pesticide concentrations at 3500 surface and groundwater sites across the UK over a period of 2 years (EA, 1995). It reported low concentrations of a wide range of pesticides in many environmental waters. Whilst pesticides are commonly considered to be a problem with lowland surface waters problems have been experienced in the uplands of Yorkshire. Williams *et al.* (1991) found simazine levels of $70\mu\text{g l}^{-1}$ in surface waters and Skinner *et al.* (1997) cite atrazine as the pesticide most commonly breaching the $0.1\mu\text{g l}^{-1}$ limit in water due to its high solubility and environmental persistence.

Breach & Porter (1995) found the most commonly detected pesticides in the supply catchments of Severn Trent Water to be the non-agricultural herbicides, atrazine, simazine and diuron, and the cereal herbicides mecoprop and isoproturon and Croll (1991) reported atrazine, simazine, mecoprop, dimethoate, isoproturon and chlortoluron in numerous surface waters.

Pesticides can be effectively removed by the use of granular activated carbon (GAC) or a combination of ozone and GAC, but both of these treatment options have both high capital investment and operating costs associated with them. These compounds are of major concern to water supply companies due to their environmental persistence, the cost of treatment involved in their removal and the serious potential public health impacts associated with their ingestion.

Present knowledge of potential source areas

Pesticides are usually targeted at particular problems or suspected problem areas. In addition, growers and land managers may apply pesticides in a precautionary manner to avoid the occurrence of an infestation. The potential sources of these can therefore be deduced from an understanding of the agricultural cropping patterns and other agricultural activities taking place within a catchment area. The most common method of application is by spraying of a pesticide solution onto the desired area (usually commercial crops). In addition, herbicides are often combined with fertilisers and spread directly onto crops and as a result, vast quantities of herbicides are used in agriculture each year. Herbicides are also commonly used on railway lines, roadsides and footpaths to control weed growth. Of the many thousands of pesticide compounds that are in use or persist in the environment, it is herbicides that are most often found in UK drinking water (Gray, 1994).

Point sources of pesticide account for very few pollution events, with by far the greatest proportion of contamination being from surface and drainflow runoff from fields and from spray drift (Anon, 1993; Skinner *et al.*, 1997). The contribution of other sources of pesticides, such as road and railway weed control have been more difficult to establish (Skinner *et al.*, 1997), but are known to exist and therefore must be considered in the identification of hazards.

Many pesticide compounds are bound within the soil layers due to their affinity to soil organic matter (Gray, 1994). The percentage of pesticides actually transported from fields to watercourses is dependant on a number of factors. The pathway of pesticides from land to water is also difficult to identify conclusively (Gomme *et al.*, 1991, 1992) although numerous models have been developed that predict the mobilisation of pesticides to surface waters (see for example, Court *et al.*, 1995). However, all of these models are extremely data intensive for their input parameters and relate only to predicting the concentrations of pesticides transported from a land area. They are therefore excessively complicated for hazard identification, as only the *potential* source areas within the catchment are under consideration here.

Building of Source Tree and GIS data model

In order to predict the occurrence of potential source areas, it was assumed that pesticides are applied at the average rates identified by the British Pesticide Usage Survey Report (MAFF, 1994). These application rates were combined with the crop information available from the agricultural census data. This subsequently produced the relative input of pesticides to the land surface for 2km grid squares in the study catchment. The application rates estimated from the literature were ranked on a scale of 1 to 5 (negligible to very high), allowing the 2km by 2km data to be subdivided into smaller spatial units using the ITE data. As with cryptosporidium hazard identification, these large cells were then subdivided using the ITE Landcover data.

ITE classes 18 (arable) and 19 (ruderal weed) were used to identify areas of agricultural arable land that could potentially have pesticides applied to them. Using this method the relative contribution of each cell area could be determined, rather than relying on absolute values from the larger resolution agricultural census data. Thus errors of scale could be minimised. The areas should not be subdivided prior to this ranking process as the original agricultural census data would be over representative of the small areas of actual agricultural land within each cell. Areas in ITE classes 5 (grass heath), 6 (mown/grazed turf), 7 (meadow/verge/semi-natural) and 9 (moorland grass) were combined in a similar way with estimated application rates from the 1993 British Pesticide Usage Survey Report (MAFF, 1993) to determine the impact of grassland applications. These were then combined with the arable inputs from above.

These data identified the hazards presented by all hydrological pathways, but as discussed earlier, the rapid mobilisation of compounds by surface runoff poses the greatest potential hazard to the quality of the surface water in the catchment. The pesticide hazard maps were therefore combined using geographical overlay (the "WITHIN" function in MapInfo) techniques with the RPI map to identify areas where the pesticides could potentially be transported from the land surface by overland flow / runoff.

Although less extensive than the diffuse input from agricultural land and weed control, point sources such as sheep-dips also present a pollution hazard to surface waters. Littlejohn & Melvin (1991) found organophosphate compounds in a watercourse 400m from their sheep-dip source, illustrating just one example of the potential for contamination from such installations. Particular problems may occur where pesticide residues are transported from surface storage areas or agricultural buildings. Techniques similar to those used when identifying point sources for cryptosporidium were used to identify these. Automated text string searches were again used where OS vector maps are available and manual searches of the 1:10,000 raster maps carried out in the remaining areas. Agricultural buildings (potential pesticide stores) and sheep dips were thus located and stored in the GIS as digital data layers.

This source identification process is represented by the Source Tree shown in Figure 7.5 a) below, and the GIS data model in Figure 7.5b).

Figure 7.5 a) Pesticides Source Tree

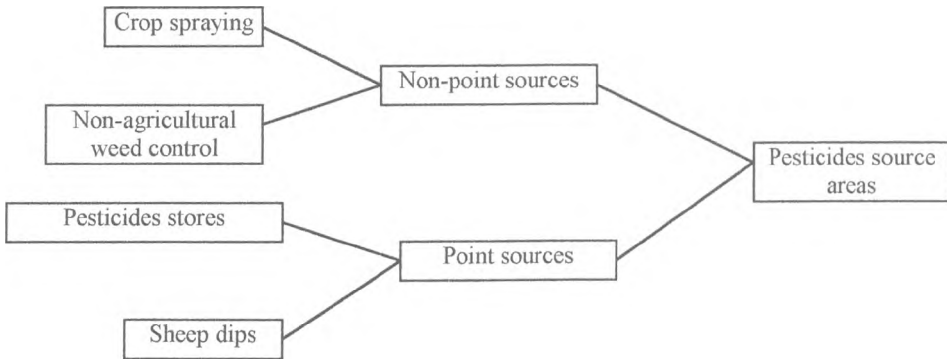


Figure 7.5 b) Pesticides GIS data model

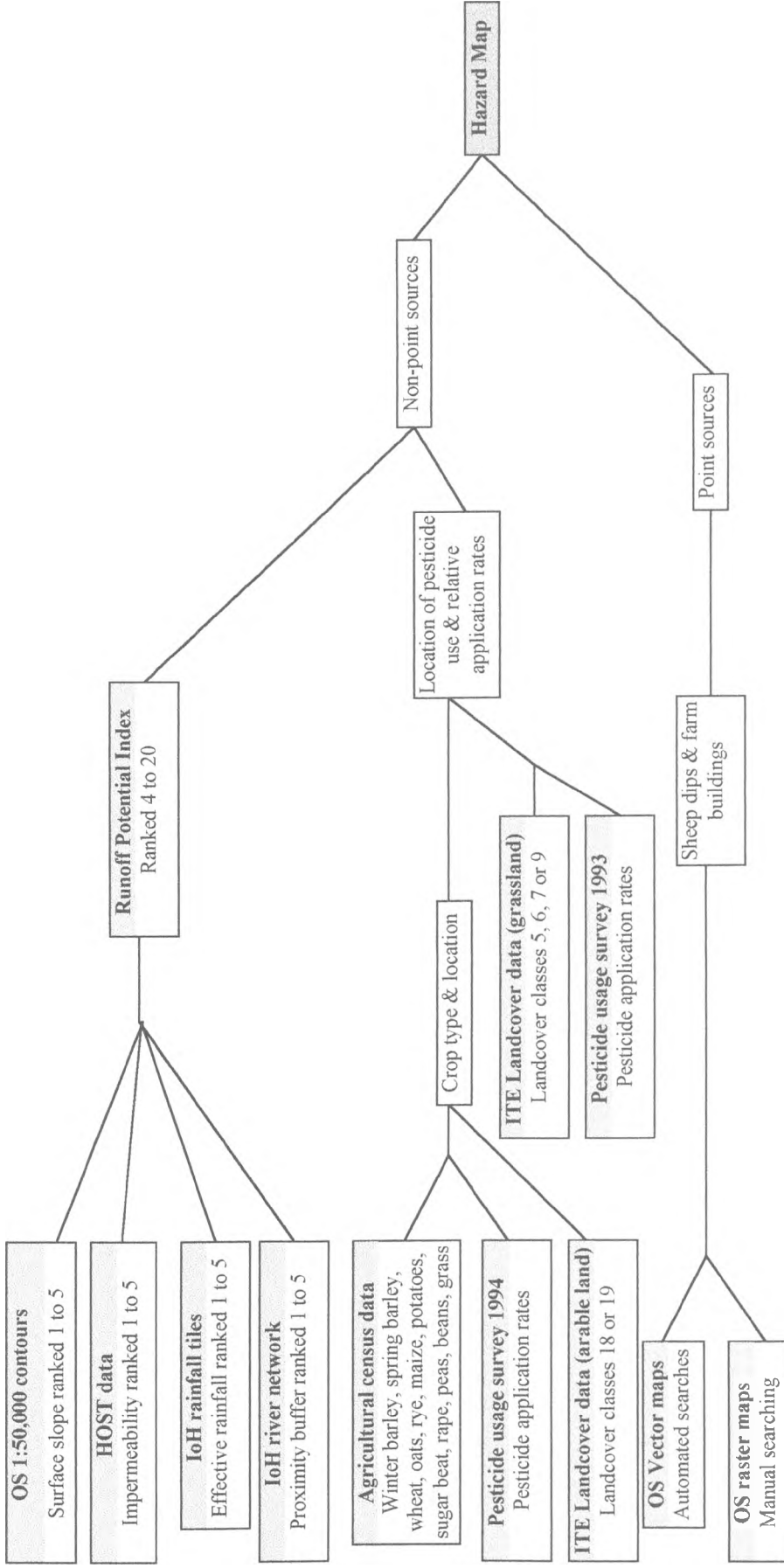
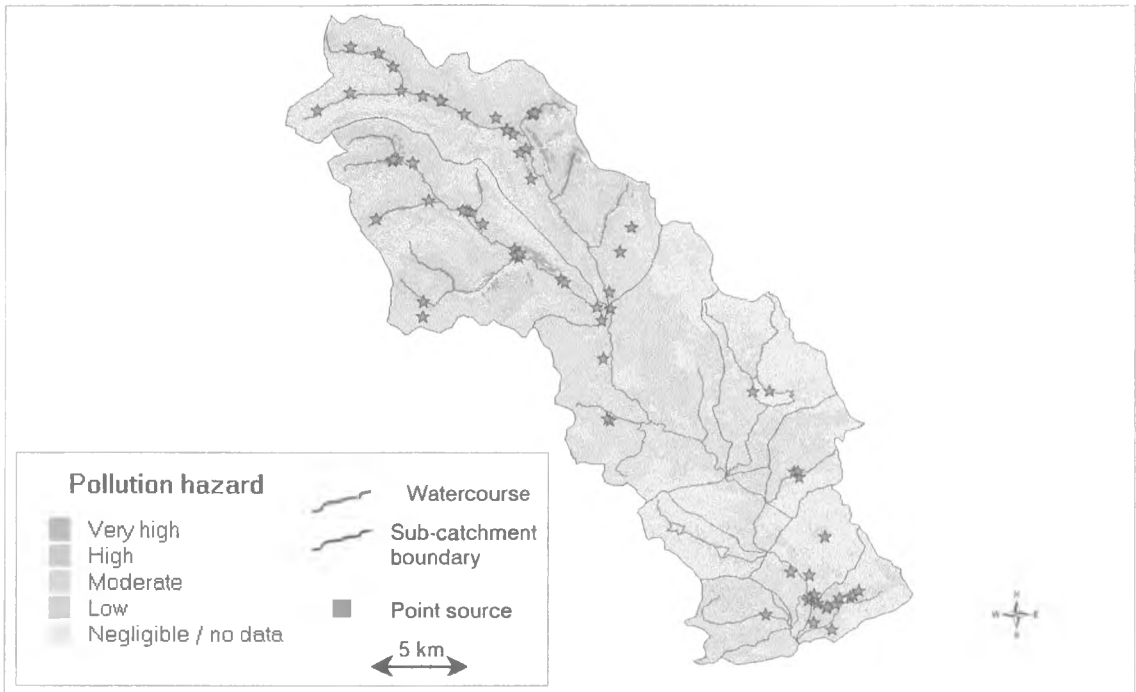


Figure 7.6 Pesticide hazard map



The pesticide hazard map shown above again illustrates the potential significance of runoff from the steep valley sides. The main hazards are found in the Langstrothdale sub-catchment in the north-east of the study area. This is due to the combination of agricultural practices and land liable to results in surface runoff. In addition, large numbers of potential point sources in the southern sub-catchments indicates a high potential hazard in these areas. The potential for major contamination due to a significant spill from a point source (e.g. a sheep dip) is therefore greater in these areas.

The majority of hazards are the result of managed grassland areas where pesticides may be applied (note the difference in distribution of hazard compared to cryptosporidium as open shrub moors are not applicable in this case). Significantly lower hazard has been identified in the Main River 1 catchment and the south-western sub-catchments of Barden and Halton due to less managed grassland and fewer point sources.

7.2.4 Oils & greases

Introduction / background

Oils and greases were identified as hazards due to their proliferation in past pollution incident records. Their primary impact on drinking water is the adverse effect on taste and odour in very low concentrations. In larger concentrations, oils and greases have potential public health impacts due to their toxicity. However, the associated taste and odour problems usually prevent customers from drinking any water contaminated with oil or grease compounds. No specific standards are stipulated in the water supply regulations for general oil and grease compounds, but contamination would be covered under the requirement to supply water that is “wholesome” (see Chapter 2).

Present knowledge of potential source areas

Oils and greases are the result of anthropogenic activities and various sources can be identified as potential hazards. These substances are primarily associated with road and rail transport activities, although static stores may exist within a catchment area. As well as being used in industrial processes, oils and greases are stored for use at garages, farm holdings and commercial premises. All such buildings could therefore be a potential hazard. The identification of commercial and industrial premises within the catchment was a priority. Additional possible point sources are car parks and vehicle standing areas and consented discharges with oil and grease restrictions. Such restrictions are usually set as zero, but the existence of the restriction indicates the presence of a potential hazard at the consented site.

Building of Source Tree and GIS data model

The limited types of sites on which oils and greases may be expected, such as those identified above, can be summarised by the source tree in Figure 7.7 a). Point sources were identified using the same methods as described above, i.e. a combination of automatic text string searches of the vector Landline maps and manual inspection of large scale raster background maps. Consented discharges with oil-based consent conditions were identified from the paper records obtained from the Environment Agency. Point features created from original text files in MapInfo allowed licensed discharges to be easily interrogated by consent conditions.

Non-point source risks from the road network in the catchment were determined from the Strategi[©] and Basedata information available through GISLAB. Individual road link features were assigned a hazard rank based on their proximity to a watercourse and the classification of the road. As with the RPI, proximity was determined automatically by buffering the river network in MapInfo. This rank was then added to a rank of accident probability. The accident ranking was based on potential for accidents to happen from statistical records (adapted from Cole & Lacey, 1988). This is discussed further when estimates of risk frequency are considered in later chapters. Figure 7.7 b) shows the structure of the GIS data model and the resultant oils and greases hazard map is shown in Figure 7.8.

Figure 7.7 a) Oils and Greases Source Tree

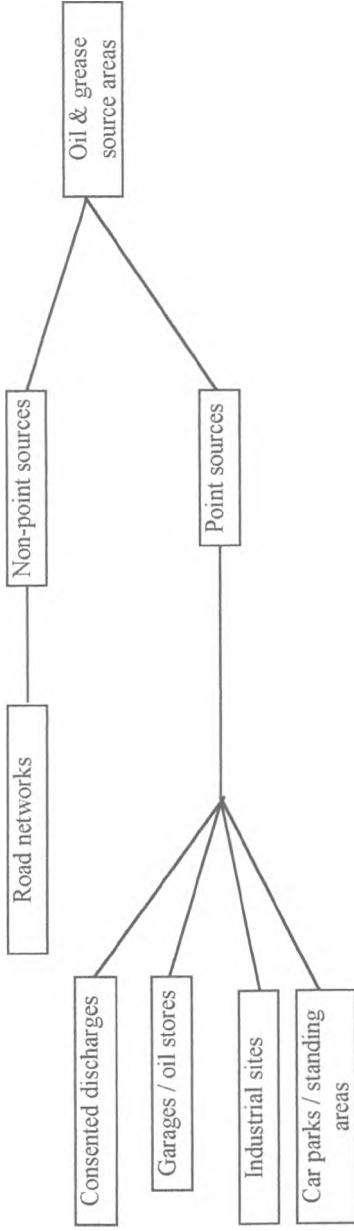


Figure 7.7 b) Oil & Greases GIS data model

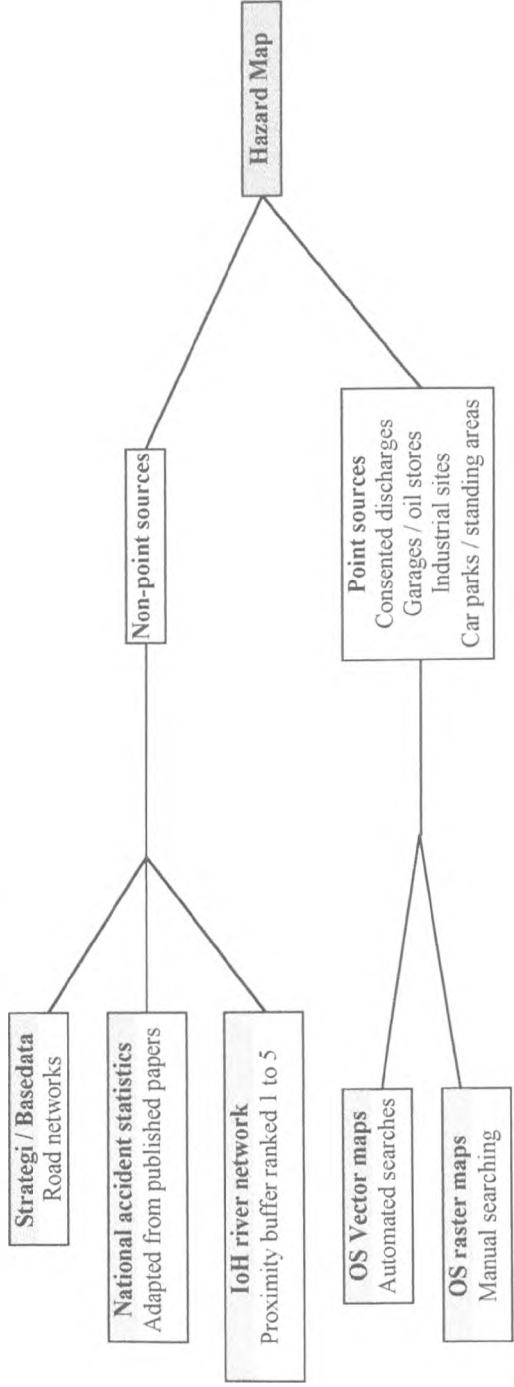
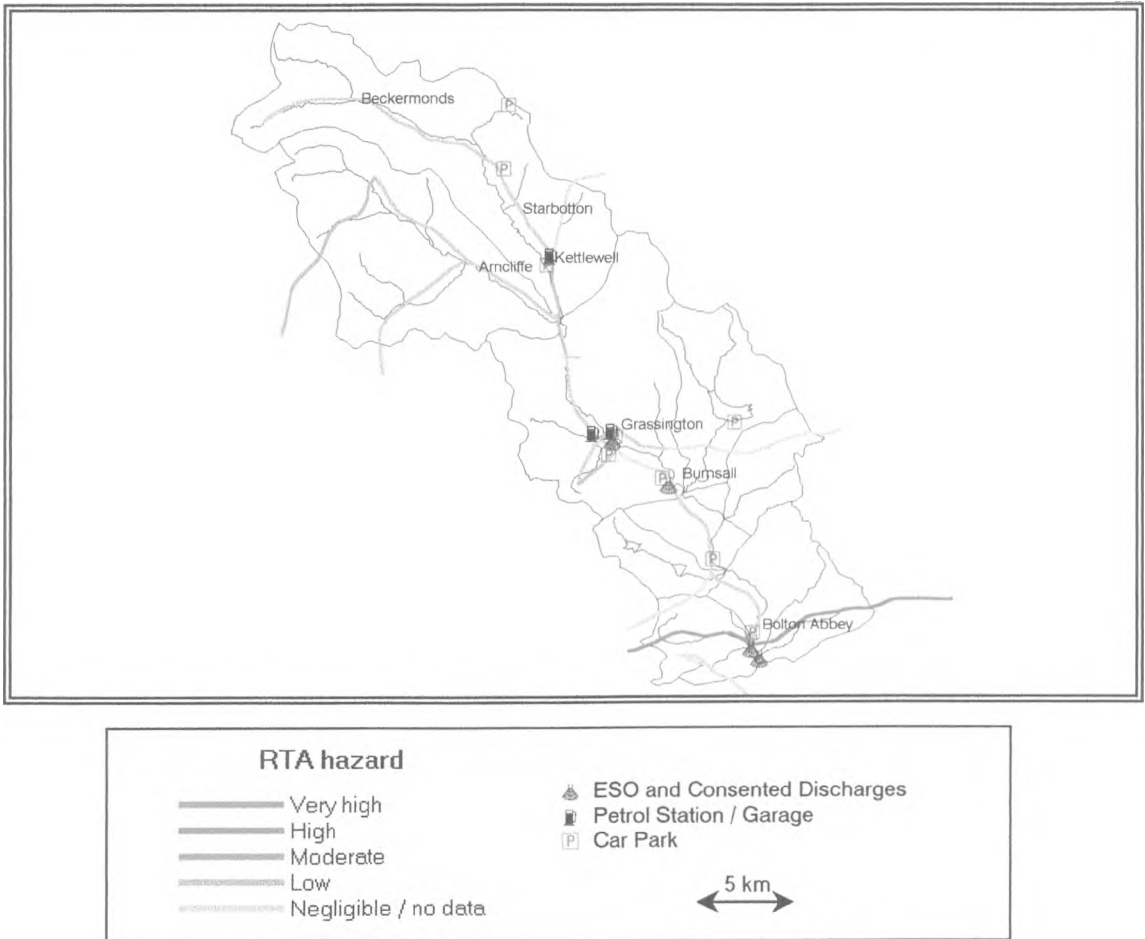


Figure 7.8 Oils & Greases hazard map



Due to the nature of the potential sources, the oil and greases hazard maps only identifies surface features that present a hazard rather than assigning a rank to all land areas. Emergency sewer overflows (ESOs) and consented discharges are identified, as are garages likely to contain stores of fuel and oils. No account is taken of domestic storage of such materials as quantification of such hazards is likely to be grossly inaccurate. However, the input of spills via urban drainage systems will be identified by a combination of ESOs and consented discharge sites.

The potential inputs from roads are identified by calculating the hazard of a road traffic accident (the most significant source of large quantities of oils) and car park sites. This could be further improved by increased use of local accident figures and visitation rates for car park sites. However, such information is not widely available, or even collected for many catchment areas and therefore belies the generic approach that is being sought after in this methodology.

The hazard map shows that the greatest hazards exists in and around the settlements in the catchment, especially Grassington. As the largest village in the catchment this has numerous car parks and garages as well as consented discharges nearby. In addition, the potential impact of the major roads, and minor roads that run close to watercourses in the headwater areas, can be seen.

7.2.5 Colour

Introduction / background

Discoloured surface waters are the result of the decomposition of organic matter forming products such as humic and fulvic acids. The resulting dissolution of organic matter can present a serious hazard to the quality of drinking water (Mitchell, 1991). The major impact on consumers is the unpleasant tainting of the water, resulting in a considerable number of complaints to the supply companies. More significantly, the chlorination of coloured waters can result in the formation of trihalomethanes (THMs) such as chloroform, which are suspected carcinogens (*Lancet*, 1981). The treatment of discoloured water to reduce these impacts involves considerable operational cost, making discoloration avoidance measures such as catchment control favourable for the sustainable management of water resources and quality.

The Water Supply (Water Quality) Regulations specify a maximum level of discoloration of 20 mg^l⁻¹ Pt-Co (equivalent to approx. 1.5 absorption units per metre at a wavelength of 400nm), which is readily visible to the naked eye.

Present knowledge of potential source areas

Considerable research has been conducted into the identification of colour source areas, mobilisation trigger conditions and the prediction of colour levels based on catchment characteristics. Work throughout the upland catchments of northern England and Wales has shown colour to be consistently related to a number of physical catchment variables (McDonald & Naden, 1987, 1988; Boon *et al.*, 1988; Mitchell, 1991; Mitchell & McDonald, 1995). High colour values have been found in water draining winter hill peat, particularly where the peat is located on shallow, south facing slopes which promote suitable microbiological activity. Naden & McDonald's (1989) study of the long term trends in discoloured water in the Nidd valley (adjacent to the Upper Wharfe) found that seasonal peaks in colour were associated with large moisture deficits during the previous months and were also associated with autumnal flushes, and high soil moisture deficits during the previous year's summer.

Recent increases in the extent of discoloration seen in upland surface waters have been associated with severe drying of peat commonly experienced during drought years. Consequently Mitchell & McDonald (1992) suggest that whilst peat erosion is not directly responsible for increase colour production, it will increase the amount of surface drying and thus enhance organic decomposition and lead to the production of discoloured water. The increased surface exposure and lower albedo of eroded, burnt and mechanically exposed peat were found to locally increase discoloration from small upland catchments. More recent research has related colour to the soil characteristics of catchments and to catchment morphometry with the specific aim of identifying relationships to form the basis of hazard maps to assist in catchment management (Mitchell & McDonald, 1995).

Catchment characteristics that have been found to promote the production and mobilisation of colour causing compounds can be summarised as: areas of Winter Hill and Maw peat soils; areas of shallow slopes ($<8^\circ$) - as low hydraulic conductivity due to minimal gravitational drainage allows maximum pick up of the colour causing solutes; south facing slopes; areas of eroded, ditched, burnt or drained peat.

Building of Source Tree & GIS data model

The source tree for colour was built up from two contributing factors, those providing the store of colour causing organics in a catchment area, and those promoting the mobilisation (release) of the discoloration. As can be seen from Figure 7.9 a), the soil type, slope and aspect will determine whether organic decomposition can take place, hence producing a colour store within the catchment. The release of this store to the surface waters will be dependant on the drying and drainage of the organic soils. This will also be enhanced by exposed peat surfaces that may result in increased microbial activity in the soil horizons.

The GIS data model in Figure 7.9 b) shows how the considerable knowledge base on colour production and mobilisation resulting from work in Derbyshire and Yorkshire catchments can be transferred into hazard maps in a GIS. As before, the slope TINs created from the OS contour data were used to identify slope ranks. These were based on the same values as the RPI shown in Table 7.1, but the rankings were reversed. As shallow slopes promote the breakdown of organic matter these were ranked 5 for colour production potential, and similarly, steep slopes given a low ranking of 1. The ARC/INFO TINs also identified slope aspect in degrees, these could therefore be ranked according to their relative contribution to colour production. The boundary values for the revised slope and aspect ranks are given in Table 7.2. Peat soils were mapped from the 100m resolution soil data, completing the necessary data for the production of a colour store area within a catchment.

Table 7.2 Rank classification boundary values for components of the catchment colour store

	Rank 1 (Very low)	Rank 2 (Low)	Rank 3 (Moderate)	Rank 4 (High)	Rank 5 (Very high)
Slope (degrees)	≥ 32	≥ 24 and <32	≥ 16 and <24	≥ 8 and <16	≥ 0 and < 8
Aspect (degrees)	North 0-45° & 315-360°	-	East & West 45-135° & 225-315°	No aspect (-1)	South 135-225°

As described above, factors promoting the release of this colour store include high drainage density, rainfall, exposed peat soils and areas of moorland burning. Drainage density can be easily determined in the GIS from the river network and sub-catchment area data. Areas of exposed peat were identified by selecting all areas of bare ground (from the ITE Landcover data) within the peat soils of the 100m soil map data. These were ranked 5 (very high). Areas where burning practices may take place were again identified from the ITE Landcover data (classes 10 and 11) and one point added to the rank of these areas.

The rainfall data available gave insufficient detail to determine periods of high rainfall preceded by seasonal deficits in moisture levels and could therefore not be incorporated in the hazard mapping variables. However, this becomes more important when considering the timing of colour release rather than just to potential for such a release to take place as is being identified here. The resultant colour hazard map is shown in Figure 7.10.

Figure 7.9 a) Colour source tree

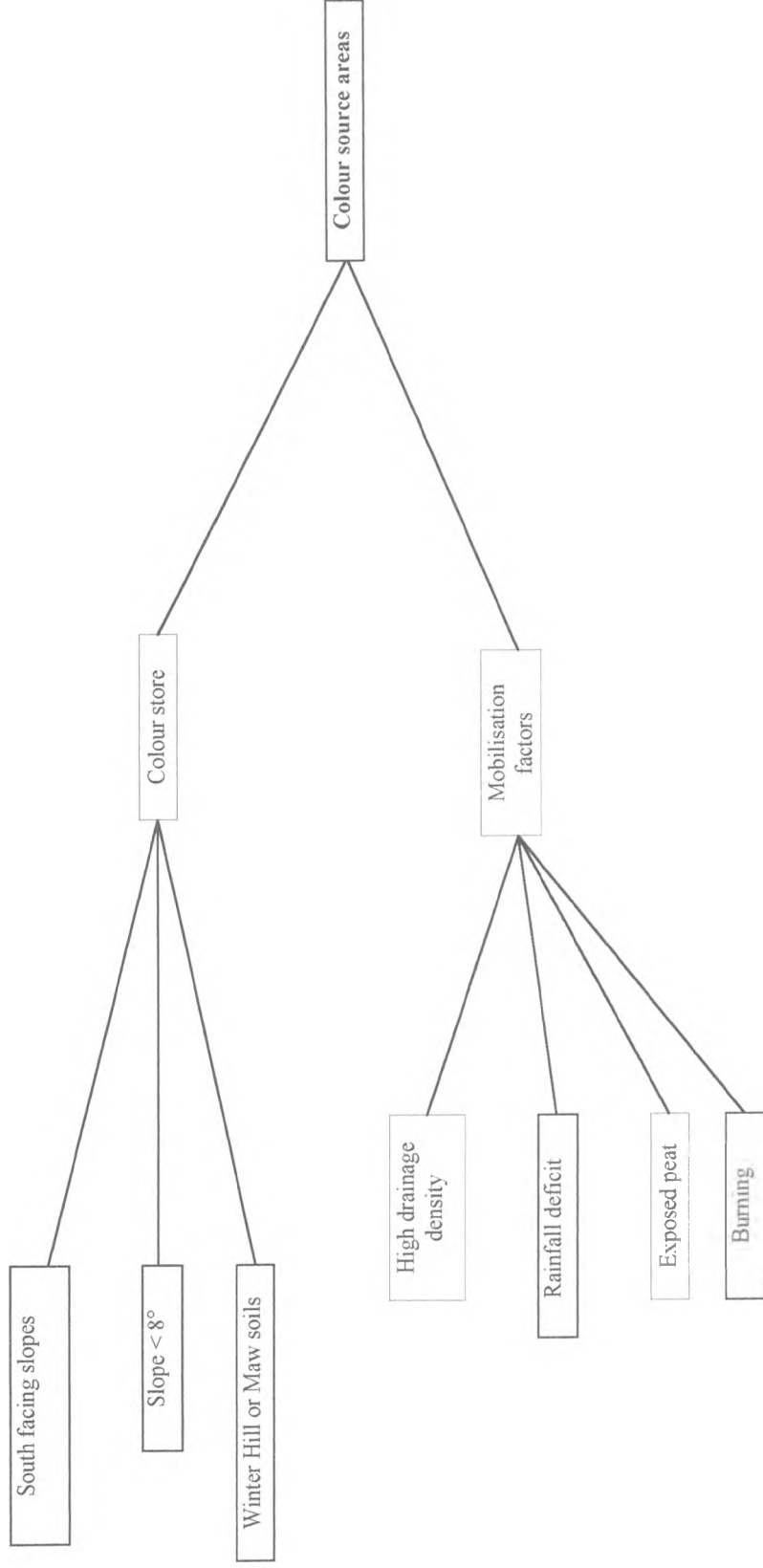


Figure 7.9 b) Colour GIS data model

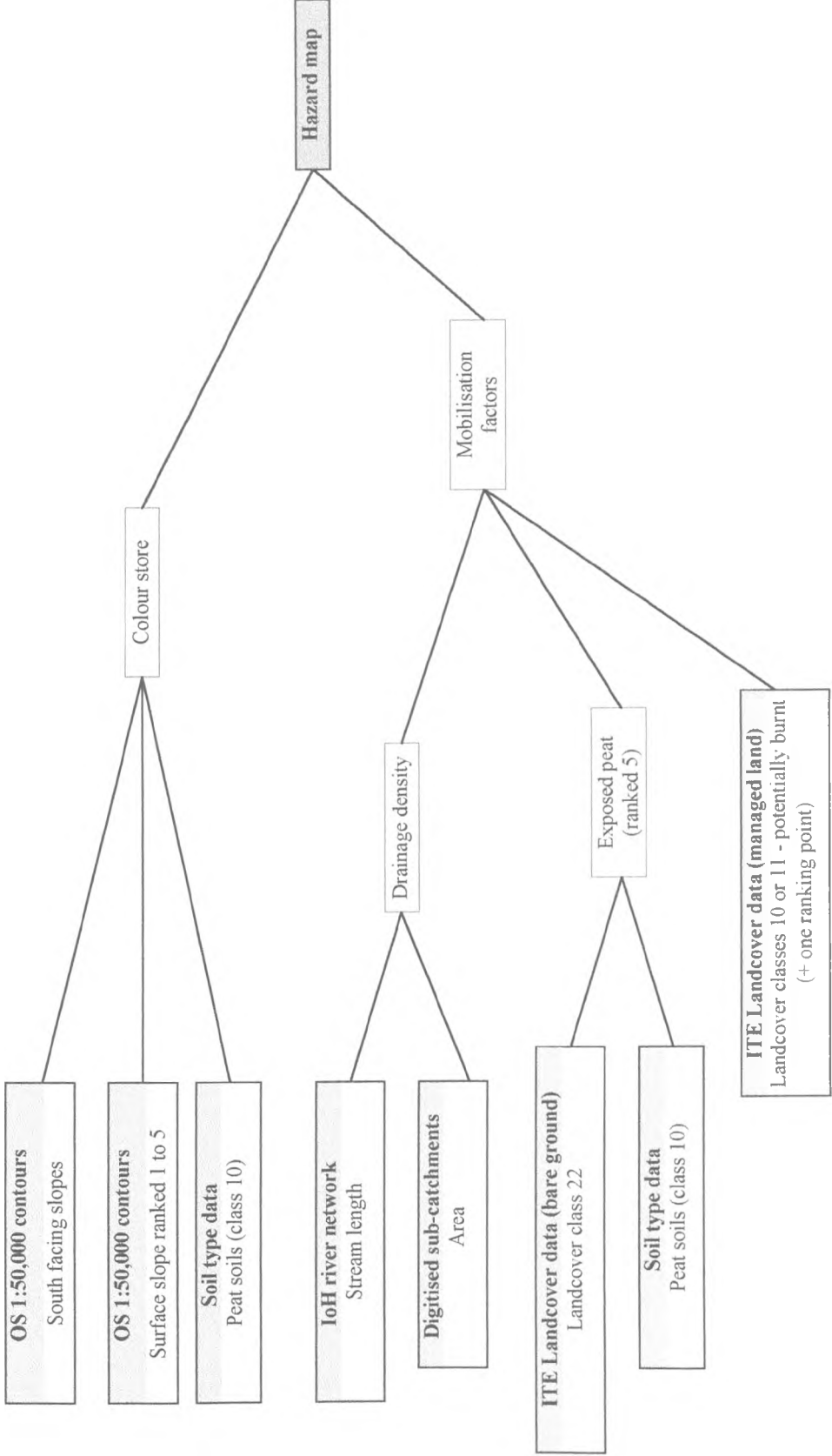
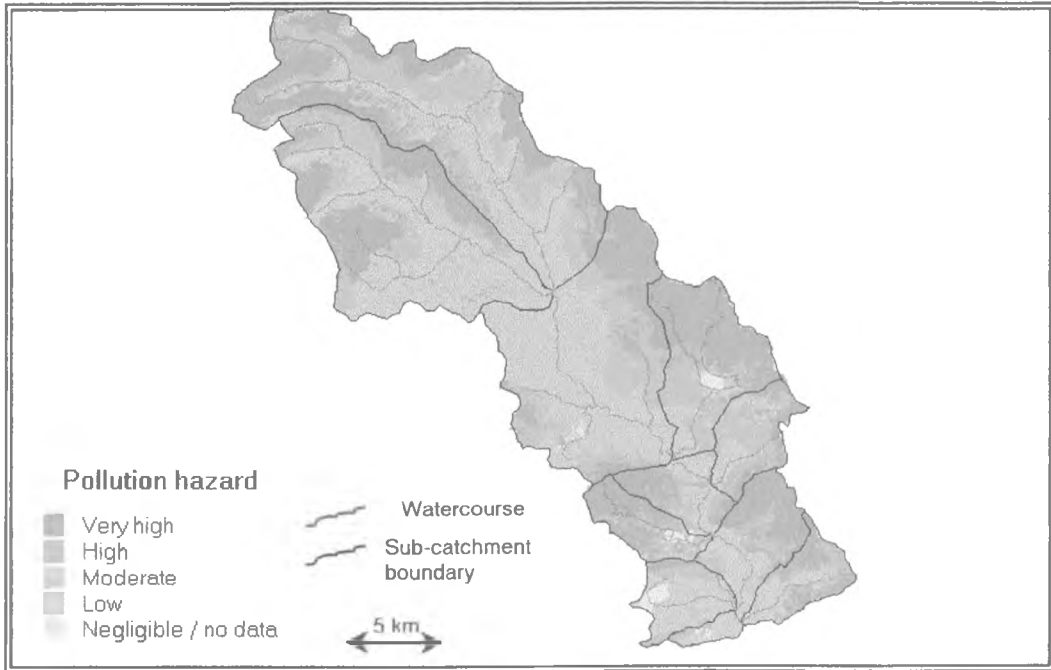
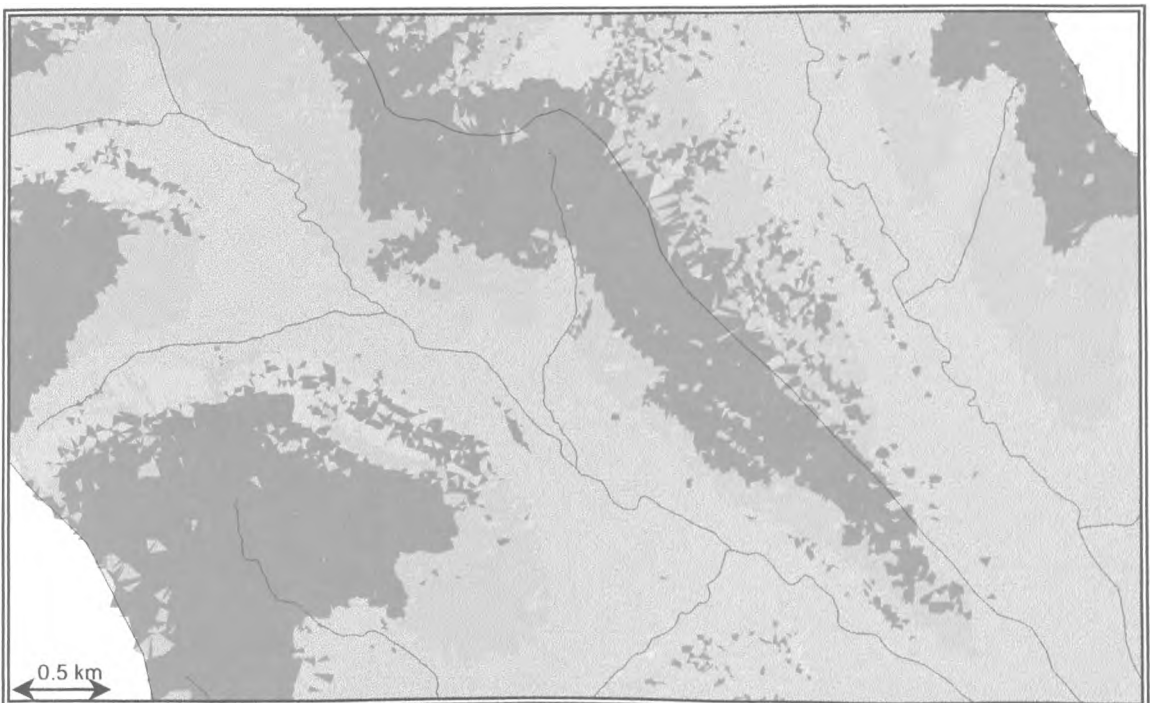


Figure 7.10a) Colour hazard map



This picture gives the overview for the catchment. Areas of “Very High” hazard can be seen around the edges of the catchment and the high moorland areas of the headwaters. These results from the large expanses of peat soils combining with conditions suitable for colour generation and mobilisation (such as south facing slopes). The following image (Figure 7.10b)) provides an illustration of how the hazard maps can be used to identify localised colour source areas within sub-catchment areas.

Figure 7.10b) Sub-catchment scale colour hazard map



Such a map can be used to clearly identify particular fields or moorland areas liable to produce discoloured water. Where available catchwater turn-out schemes can be identified so these waters are not used for potable abstractions, or colour-enhancing activities, such as ditching and surface erosion can be reduced by alternative management practices.

7.2.6 Trace Metals

Introduction / background

Trace metal elements are those which occur at levels of below 1mg l^{-1} in natural waters, for example aluminium, manganese, copper, lead and mercury. These can exist in various different forms (or species) with varying toxicity. For example, free aqueous copper ($\text{Cu}^{2+}(\text{aq})$) is the most toxic form of copper.

These elements are of particular importance due to their abundance in the natural environment and relatively little knowledge of their mobilisation factors in upland water gathering grounds. They are so ubiquitous in nature that many water supplies will be influenced by their presence, but upland surface waters are particularly vulnerable due to the lithology and pedology of the catchment areas.

As seen in Chapter 2, over recent years trace metal elements have accounted for a high proportion of failures of the Drinking Water Regulations in the YWS operational area, especially in the early 1990's. Those of greatest significance are Iron, Manganese, Aluminium and Lead. Lead failures are usually associated with the uptake of contamination from old mains and service pipes and can usually be addressed by a mains replacement programme or by dosing trace levels of orthophosphoric acid to reduce plumbosolvency. However, some investigation of lead pollution hazard is carried out later due to specific problems seen in the Wharfe catchment. Elevated levels of iron, manganese and aluminium in drinking waters may result from elevated levels in source waters.

Iron

Iron (Fe) is a commonly found element in rocks and soils and can be incorporated into passing water where reducing conditions convert the insoluble ferric iron (Fe^{3+}) to form soluble ferrous iron (Fe^{2+}) (Gray, 1994). As a result iron is commonly associated with groundwater sources where it is present in the soluble ferrous form. In upland catchment areas wet, acidic conditions promote the reduction of the insoluble ferric iron and release of mineral ions into the hydrological system. The oxidation of a proportion of these ions in the surface waters can then result in the presence of insoluble ferric iron particles as well. The primary problem associated with iron is the discoloration of supplies to consumers, which can lead to levels of service failures and complaints, especially where the discoloration of washing or food results. The presence of ferric iron in drinking waters can lead to the deposition of ferrous particles in the distribution network.

Iron has a low taste threshold and can cause taste problems, especially in beverages made with water direct from the tap (Gray, 1994). As an essential element iron is unlikely to cause health problems at the levels experienced in UK drinking waters. The threshold of taste is approximately the same (0.3 mg/l) as the guideline level of the World Health Organisation. The EC Drinking Water Directive MAC level is 0.2mg l^{-1} ($200\mu\text{g l}^{-1}$), as is the UK prescribed concentration value.

Manganese

Manganese (Mn) is also naturally occurring in ores and rocks and like iron is brought into solution in reducing conditions. High concentrations of manganese often occur in association with elevated levels of iron due to the similarities in behaviour of the two metals (Heal, 1997). However, manganese is generally more mobile than iron due to the less extreme pH and redox potential conditions required to reduce the insoluble Mn(IV) to the soluble Mn(II) form. In recent years, 6% of customers supplied by Yorkshire Water Services Ltd. experienced failures due to manganese (The Times, 1995) and the significant number of failed samples was highlighted in Chapter 2. A particularly high number of failures due to manganese have also been experienced in Scotland where the majority of supplies are from surface waters (Scottish Office, 1993).

As with Iron, the oxidation of soluble manganese to the insoluble form can lead to manganese deposition in the distribution network. Staining caused by manganese contamination is more severe than that associated with Iron as the particulate manganese is brown or black in colour. As a result a much stricter PCV of 0.05mg l^{-1} ($50\mu\text{g l}^{-1}$) has been set. The low taste and discoloration threshold of manganese ensure that contaminated water will generally be rejected by consumers long before adverse health effects are experienced (Gray, 1994) although high levels have been associated with neurological disorders. The WHO recommended health-related guideline is 0.1mg l^{-1} .

Aluminium

Like iron and manganese, aluminium (Al) is an extremely common naturally occurring element. It is found in all types of soil, plant and animal tissue and is frequently present in solute form in water draining from a variety of soil and rock types. Aluminium is particularly prevalent in surface waters where acidification in poorly buffered soils increases the amount leached. High levels of salt in precipitation can also enhance aluminium leaching (Gray, 1994).

Elevated levels of aluminium in surface waters are known to be toxic to salmonids (Stoner *et al.*, 1985) and have also been linked with Alzheimer's disease (a degenerative neurological disorder) in humans (Forbes & MacAiney, 1992). The Water Supply (Water Quality) Regulations 1989 stipulate a prescribed concentration value of 0.2mg l^{-1} for drinking waters, the same as the WHO recommended limit. No limit is set for aluminium in the regulations regarding the quality of surface waters abstracted for drinking water, probably because aluminium sulphate (alum) is commonly added as a coagulant in the treatment of surface waters.

Present knowledge of potential source areas

Due to the reducing conditions that are required for the soluble form of all these metal ions to exist within soils, wet, acidic conditions are generally required to mobilise these metals. The three soil characteristics having greatest control over trace metal availability and release are therefore pH, organic content and moisture content.

Soil characteristics are known to be the controlling factor over the release of trace metals from upland catchment areas. Grieve (1985) found a strong positive correlation between iron and dissolved organic matter and Boon *et al.*, (1988) found a significant positive correlation between iron levels and the area of peat in a catchment. Iron is therefore closely linked to the organic content of the soil, as well drained, alkaline soils encourage the iron to remain in the immobile ferric form. Soil conditions that favour the release of iron will also favour the release of soluble manganese due to their similar chemistries. Concurrent findings were also reported by Mitchell & McDonald (1992a; 1995) who found iron and manganese levels in North Yorkshire catchments to be related to the extent of organic soils.

Recent work by Heal (1997) has provided an increased understanding of the chemical and microbiological processes determining the release of manganese in upland areas. It was found that in larger catchments, high surface water manganese levels were related to microbial activity in soils with high organic content (peats). Aluminium by contrast is not affected by redox reactions in the same way as iron and manganese and soil pH is likely to be the dominate factor controlling its release.

The source areas of all these metals may vary seasonally due to the important impact of soil hydrology on their mobilisation. However, the hazard maps created here are intended to give an overall scenario of *where* trace metal problems may come from within the catchment area. Source areas are therefore identified from the catchment and soil characteristics described above.

Building of Source Tree & GIS data model

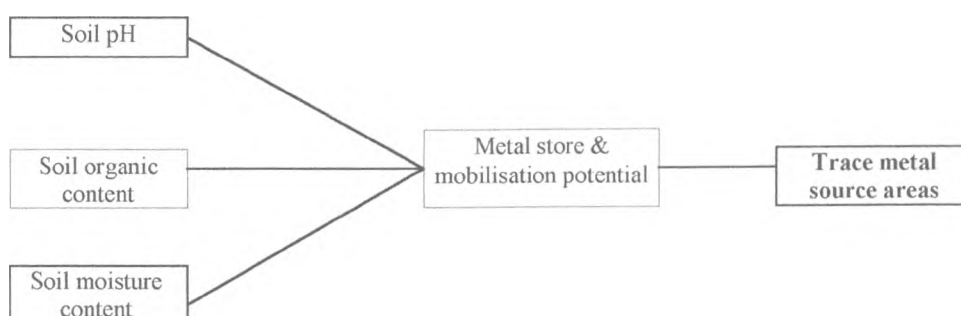
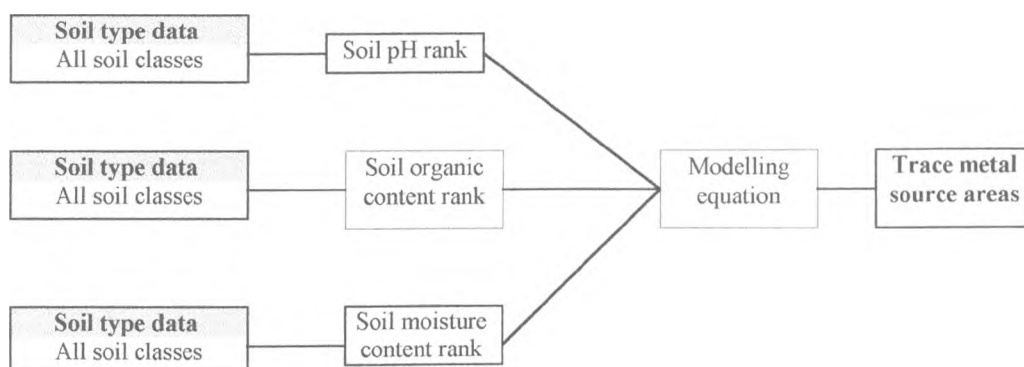
The basic controls over the production and mobilisation of aluminium, iron and manganese are the characteristics of the soil series within a catchment. Point source inputs of aluminium, iron and manganese are thought to be negligible in the Upper Wharfe catchment due to the high non-point source potential of large expanses of peat soils.

Rankings of the soil attributes describing organic content, pH and moisture content were constructed for each soil association in the catchment area from the descriptions given by the Soil Survey in the digital dataset key. For each trace metal, these rankings were then weighted to represent the relative importance of organic matter, pH and moisture content on their production and mobilisation, hence identifying the potential store of iron, manganese or aluminium. The equations in Table 7.3 show how the relative importance of different factors is used to weight the rankings for the three metals.

Table 7.3 Modelling equations for trace metal hazard map rankings

Trace element	Modelling equation
Iron	Fe rank = (soil pH rank x 1) + (soil moisture rank x 2) + (soil organic rank x 3)
Manganese	Mn rank = (soil pH rank x 2) + (soil moisture rank x 1) + (soil organic rank x 3)
Aluminium	Al rank = (soil pH rank x 3) + (soil moisture rank x 2) + (soil organic rank x 1)

Mobilisation is primarily controlled by the soil characteristics as discussed above, and the degree of mobilisation is therefore inherent in the ranking created by the equation. Figure 7.11 a) below shows the simplistic source tree for trace metals and Figure 7.11 b) shows how these data were manipulated within the GIS to identify iron, manganese and aluminium hazard areas within the catchment.

Figure 7.11 a) Trace metals source tree**Fig 7.11 b) Trace metals GIS data model**

The resultant hazard maps (Figures 7.12 a) to c)) are very similar for all three trace metals, although minor differences resulting from the ranking of soil characteristics can be seen in some places.

Figure 7.12a) Iron hazard map

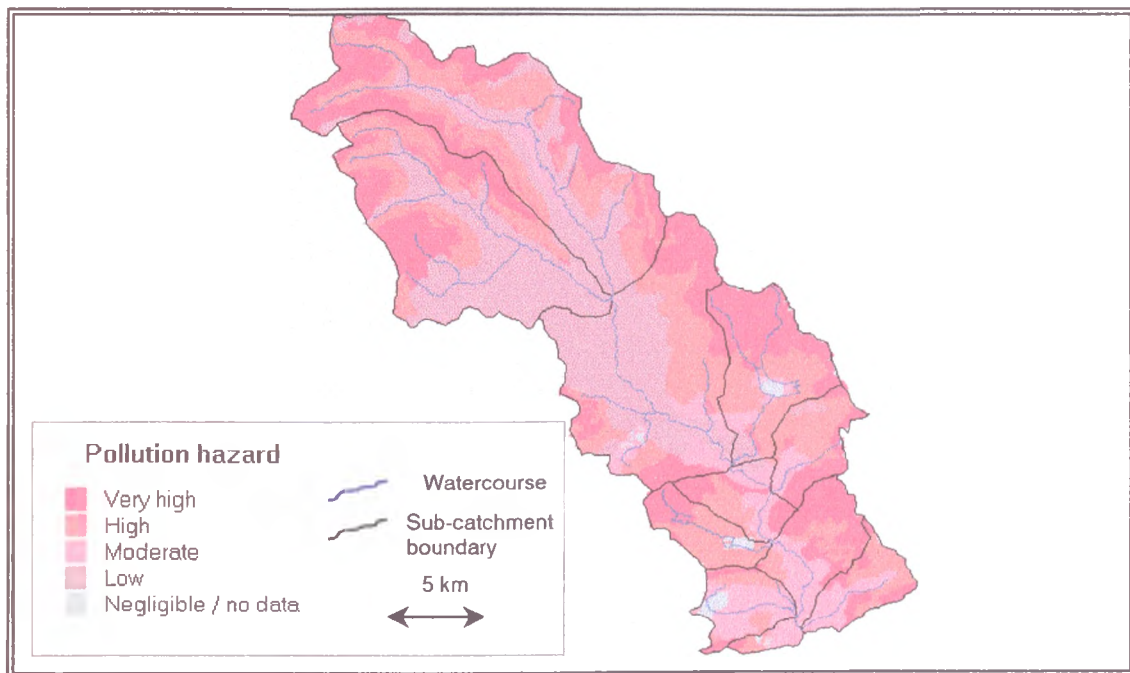


Figure 7.12 b) Manganese hazard map

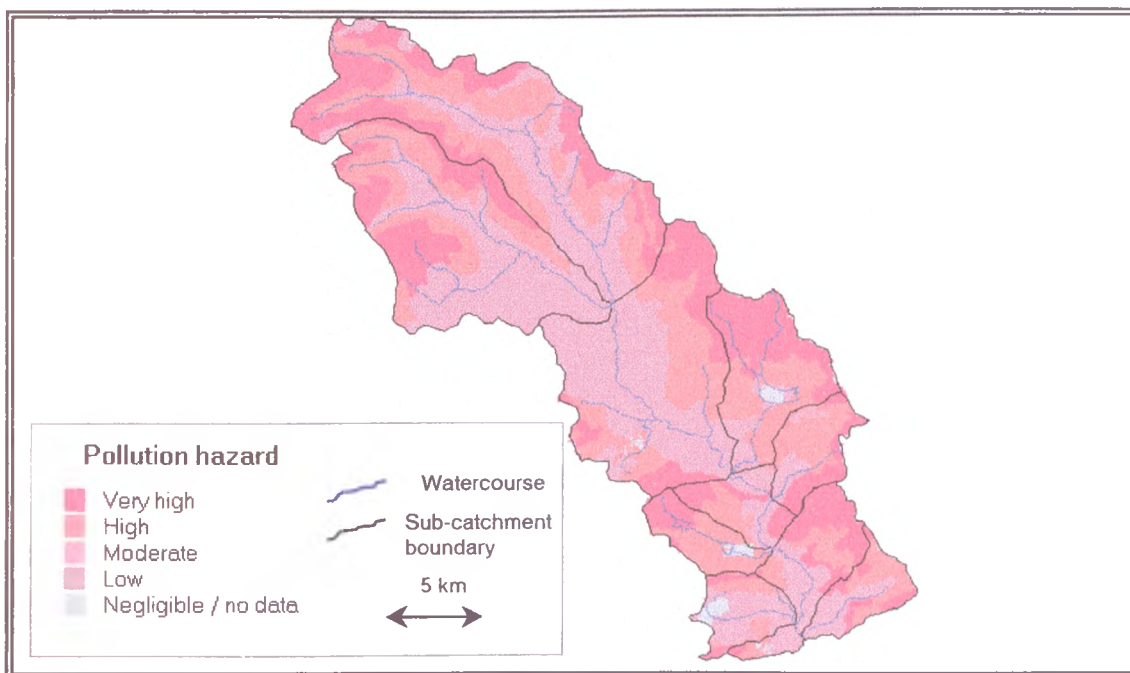
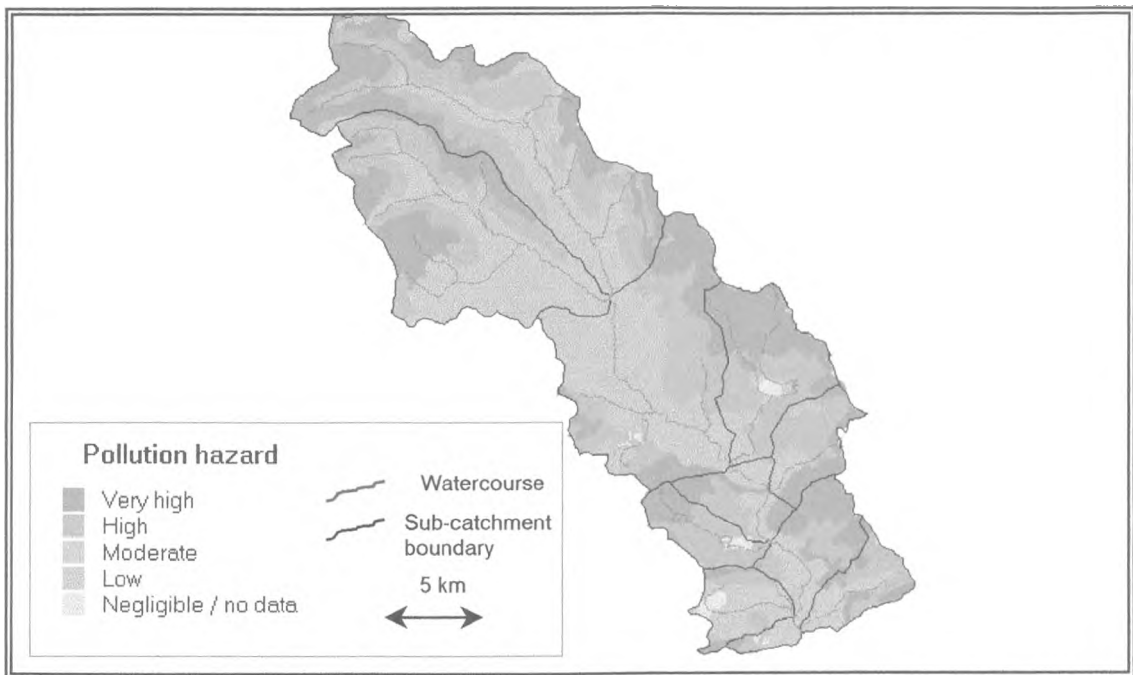


Figure 7.12 c) Aluminium hazard map



These three hazard maps show very little difference between the potential source areas of iron, manganese and aluminium. This was to be expected as they all occur under similar conditions. However, the different impact that soil conditions have on metal mobilisation can be seen in the lower (southern) sub-catchments where the land adjacent to the river presents a moderate hazard of iron mobilisation but low manganese and aluminium hazard. In general, those sub-catchments representing the greatest hazard to water quality from trace metal contamination are in the headwater areas of the Grimwith, Barden and the Main River 3 sub-catchments characterised by extensive moorland peats.

7.2.7 Faecal bacteria

Introduction / background

A number of bacteria are known to pose direct risks to public health if ingested via drinking water. Among these are *salmonella*, *campylobacter spp.* and *escherichia coli*, which can all cause serious gastrointestinal infections. Various indicator organisms are used to demonstrate the existence of a faecal-oral pathway.

The EC Drinking Water Directive and the resultant UK Regulations require that faecal bacteria (total coliforms, faecal coliforms and faecal streptococci) be absent from drinking water, and there must be less than one sulphate reducing clostridia per 20ml.

Disinfection processes during treatment are extremely effective at removing these bacteria prior to distribution, but many thousands of these bacteria may be present in a litre of raw water. The existence of such bacteria illustrates a potential contamination source and therefore possible pathway for disease transmission.

Present knowledge of potential source areas

The basic source areas of faecal bacteria are associated with the location of animal and human populations. Bacteria will be present in effluents from sewage treatment works (STWs) and in surface runoff from paved surfaces and urban areas (primarily due to domestic animal faeces). The primary source in rural catchments is likely to be non-point source overland flow from agricultural land. This may carry faecal bacteria deposited as a result of animal grazing or the spreading of wastes on the land surface. McDonald *et al* (1984) showed that bacteria concentrations were several orders of magnitude higher during storm hydrographs than in baseflow conditions, and were attributed to land stores mobilised by overland flow events. This research (McDonald *et al.*, 1984) also highlighted the importance of channel bed stores during artificially induced hydrographs. McDonald *et al.*, (1984) therefore stress the importance of both land surface stores and bed stores in contributing to increased levels of bacteria during storm events.

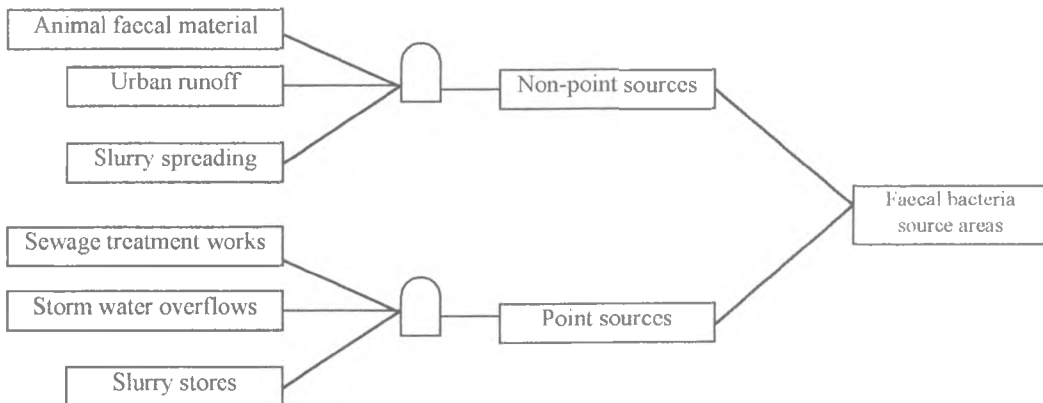
The risk assessment approach taken in this study concentrates on identifying and managing the initial hazards in the catchment area. Whilst the potential hazard presented by existing channel bed stores of bacteria is therefore recognised, consideration here will focus on the initial sources of the faecal bacteria, i.e. the land store component of McDonald *et al.*'s (1984) conceptual model of bacteria flows and stores in a catchment area. (The potential for significant risk reduction exists with these sources as catchment management activities may mitigate the risks presented by these sources). McDonald *et al.*, (1984) discount hydrological throughflow (except for macropore flows) as a transport mechanism for faecal bacteria due to the death rate of organisms within the soil. They suggest that throughflow mechanisms result in organism filtering rather than transport. Overland flow or runoff can therefore be considered the dominant transport factor when considering impacts on water supply abstractions.

Microbial inputs to the stream baseflow may originate from sewage discharges and point sources such as drains, foul sewers, manure heaps and combined sewer overflows. During stormflow events, contaminated overland flow may make a significant contribution to the faecal indicator organism levels in a stream. These will therefore be related to the location of urban areas (and effluent discharge points), animal grazing patterns and the spreading of animal wastes. Work by Wyer *et al* (1996) also highlights the significance of diffuse land sources to faecal organism levels in a stream as compared to the relatively minor input from a STW during high flows.

Building of Source Tree and GIS data model

The discussion above has identified the importance of both point and non-point sources of faecal bacteria, as shown in Figure 7.13a). Non-point sources include runoff from urban areas as well as agricultural inputs from grazing animals and the spreading of animal wastes. Potential point sources include discharges to the watercourse from STWs and storm water overflows, as well as stores of faecal material on agricultural land.

Figure 7.13 a) Faecal Bacteria Source Tree



The way in which the hazard maps were constructed can be seen in Figure 7.13 b). The agricultural census data were used in combination with loading rates from the literature (Heal, 1997 *Pers Comm*, MAFF, 1991) to identify the potential faecal input from animal sources. The likely location of these animals (i.e. grazing land) were identified from the ITE Landcover data as for the cryptosporidium hazard map. In addition it was seen from field visits that the majority of slurry spreading activities took place on areas of improved, or periodically grazed pasture. The loading of faecal bacteria will increase dramatically when calves and lambs are on the catchment, or when spreading activities are taking place. In order to address this, the total number of animals (including calves and lambs) and their associated faecal production rates are used. It was assumed that all faecal material produced is deposited on or near the animal grazing areas, either as direct deposition, or from slurry spreading activities.

Urban sources were identified from the Boundary data and the road network data used to locate roads and bridges. This enabled any points where roads or urban areas crossed watercourses to be identified. All inputs other than direct surface runoff from such areas should be addressed by consideration of point sources from the surface assets database. This holds information on combined and emergency sewer overflows and was combined with the discharge consent information for STWs.

Figure 7.13 b) Faecal Bacteria GIS data model

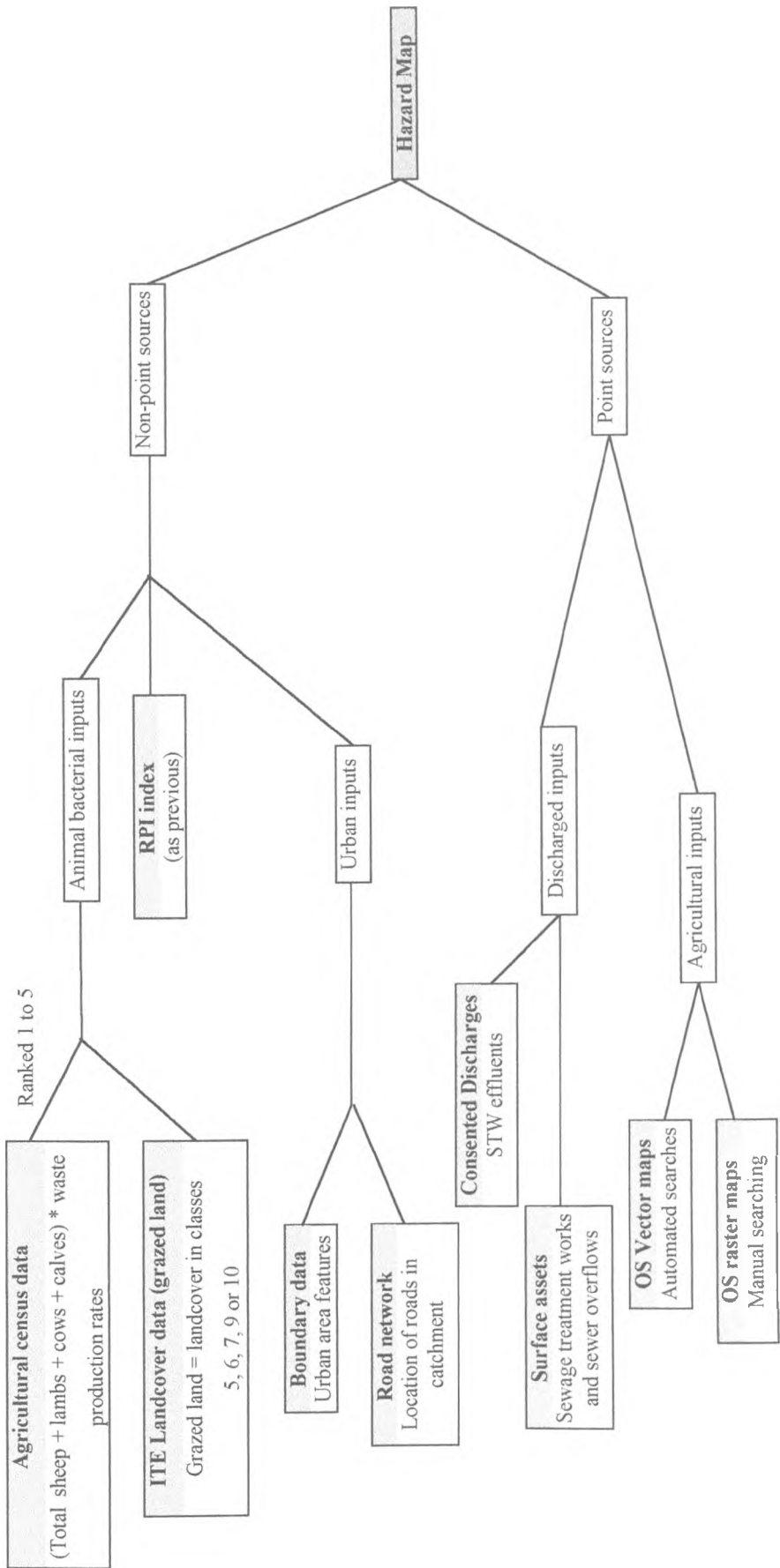
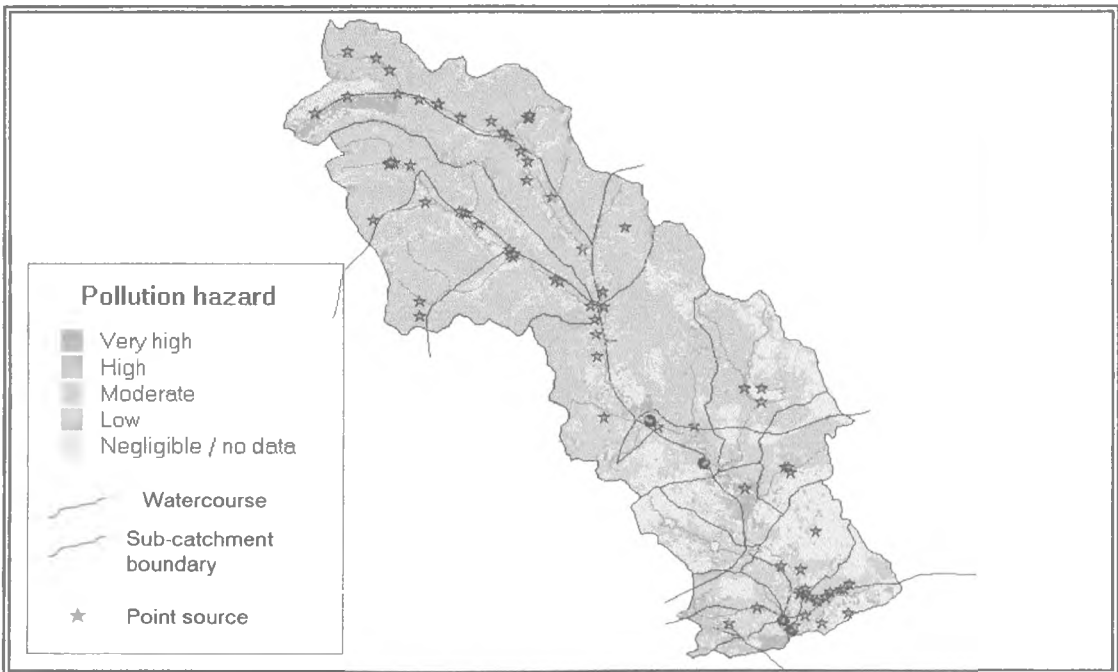


Figure 7.14 Faecal bacteria hazard map



Generally the areas of higher hazard can be found in the northern sub-catchments, although even here the hazard is not classified “Very High”. This is due to the high number of animals in these areas, but as they are spread out over a large grazing area the potential hazard is reduced. Small areas of very high hazard are present in other sub-catchments (such as Main River 4) where high stocking density and high runoff potential are found together. There are a high number of potential point sources of bacteria in the catchment with numerous STWs and sewer overflows in the upper sub-catchments and several farms and animal holding areas in the southern reaches.

The hazard map is significantly different to the cryptosporidium hazard map as the potential hazard is not influenced by infection rates (even a small number of young beasts can greatly increase cryptosporidium hazard due to their high infection rates). The non-point source agricultural and animal inputs are based only on the stocking densities identified from the agricultural census data. As such the influence of the coarse 2km by 2km agricultural census data can be clearly seen on the map. Although these areas have been sub-divided using the ITE Landcover data the impact of the coarse scale is evident, illustrating one of the problems of using a variety of data sources for pollution hazard prediction.

7.2.8 Lead

Introduction / background

The current standard for Lead (Pb) in drinking water (as stipulated in the UK regulations) is $50\mu\text{g l}^{-1}$. This may be reduced to $10\mu\text{g l}^{-1}$ in the near future, as a result of increasingly stringent European legislation. These changes are in response to a comparable decrease in the revised WHO guidelines (WHO, 1993a). Lead is easily absorbed by the human body. Young children and foetuses readily absorb lead and are therefore particularly at risk from increased ingestion through drinking water. Studies in Glasgow related high levels of lead in mothers' drinking water to increased numbers of stillbirths and mentally retarded children (Gray, 1994).

Whilst much of the lead found in finished drinking water is a result of contamination in the distribution system from lead pipes, increasingly stringent standards enhance the need to reduce initial inputs from catchment sources. The study of historical data in previous chapters has identified the Upper Wharfe as experiencing periodically high levels of lead in the river water. Some of the peaks seen in the raw river water were well in excess of the proposed revisions to the drinking water quality standards (up to $36\mu\text{g l}^{-1}$). Following filtration these values were reduced by an order of magnitude, indicating the importance of iron bound to suspended particles.

Present knowledge of potential source areas, building of Source tree and GIS data model

There are three potential sources of lead in upland catchments, industry, mining spoil heaps and deposits and the underlying geology (Figure 7.15 a). A number of industrial activities involve the use of lead, although no such industry is known to exist in the study catchment (see previous chapter). Lead may be present in water as a result of water flow over galena bedrock, however the surface lithology of the Upper Wharfe is sandstone and millstone grit and the direct contamination of surface from this source is therefore unlikely (hence absence from Figure 7.15 b).

An additional source of contamination is from spoil heaps associated with lead mining activities. A number of disused mines are known to exist in the Upper Wharfe catchment and these are therefore potential hazards. These sites were identified from automated and manual searching of the Ordnance Survey maps as they represent localised point sources. The high content of lead bound to suspended particles also indicates that the erosion of contaminated spoil heaps may present a significant hazard.

Recent work (e.g. Macklin, 1996; Macklin *et al.*, 1997; Hudson-Edwards *et al.*, 1997) has illustrated the importance of alluvial floodplains as a source of heavy metals. Discharge events can lead to these sediments being reworked and incorporated into the suspended sediment content of the river. Although these represent a significant source for riverine concentrations, they are not shown on the resultant hazard map as treatment processes (such as filtration) will remove suspended solids and as such these sources should have a negligible effect on the resultant drinking water quality.

Figure 7.15 a) Lead Source Tree

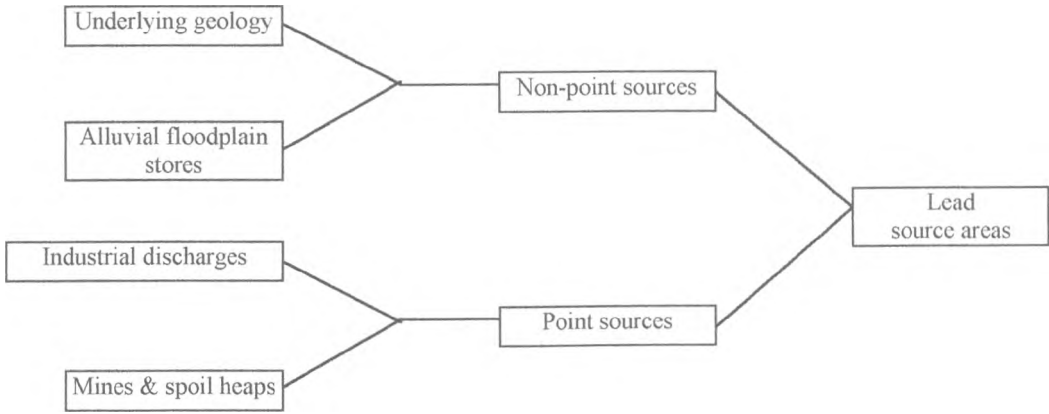


Figure 7.15 b) Lead GIS data model

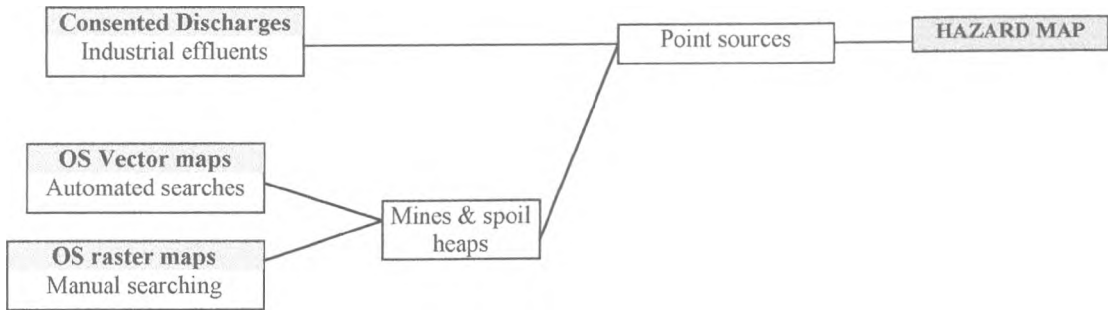
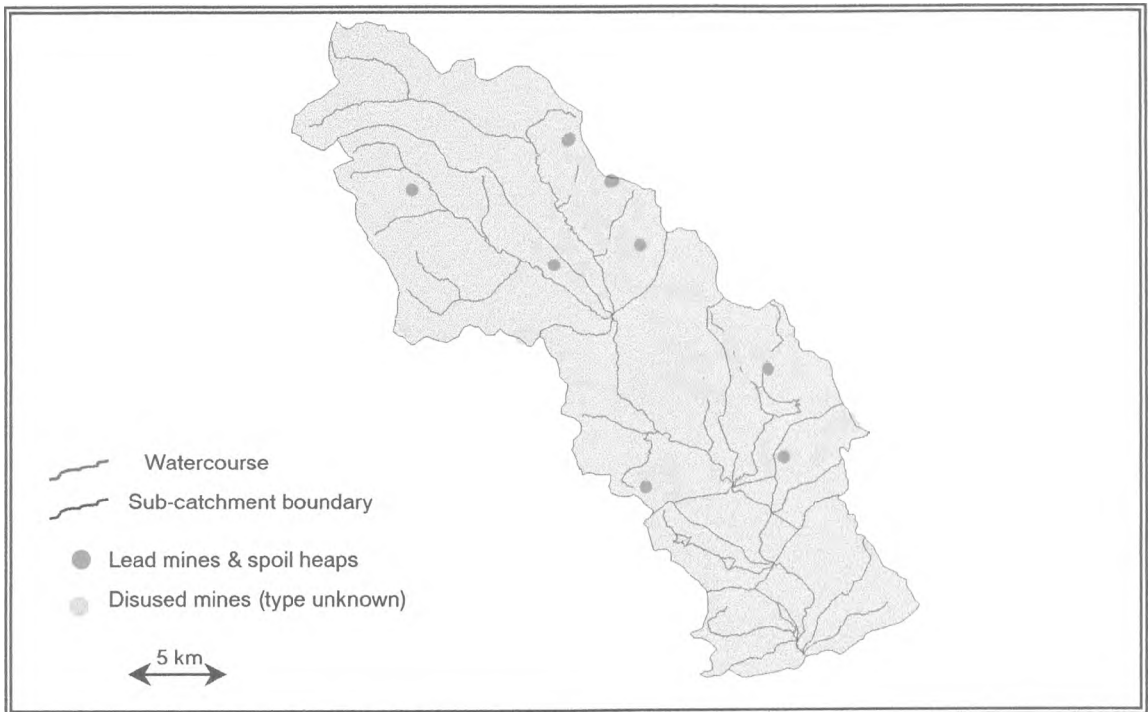


Figure 7.16 Lead hazard map

The hazard map above identifies a number of potential point sources of lead contamination. Numerous mines are evident in the catchment and three spoil heaps from lead mine workings are located in the Langstrothdale sub-catchment. Interestingly, many of the mine workings are located close to watercourses. The hazards identified on this map may be responsible for the high levels of suspended lead identified in the sample results discussed in earlier chapters. No problems of scale were experienced when identifying lead hazards as only point data were used

7.2.9 Nutrients

Introduction / background

Three nitrogen-related compounds are of concern to drinking water quality: nitrate, nitrite and ammonia. The oxidation of ammonia will form nitrite, further oxidation of which will form nitrate. Similarly, the reduction of nitrate forms nitrite and subsequently ammonia. Nitrites can therefore be formed from the contamination of source waters by ammonia, or nitrate.

Nitrates are a common element of many foodstuffs, especially vegetables, however drinking water can be a significant component of daily nitrate intake (Gray, 1994). The major public health consideration of high nitrate levels in drinking water voiced in the literature is that of methaemoglobinaemia in infants. This is also called 'blue-baby syndrome' as it can affect infants fed on bottled milk prepared with high nitrate water.

When nitrate is reduced to nitrite, this can combine with the haemoglobin in the blood to form methaemoglobin (McDonald & Kay, 1988). This methaemoglobin is unable to carry blood around the body and therefore results in a blue tinge to the skin. The progression of oxygen deprivation from this condition can induce a coma and eventually lead to death, although this problem rarely occurs in modern bacteriologically pure mains water (Gray, 1994). High nitrate levels in drinking water have also been linked to the occurrence of cancer (Shuval & Gruener, 1972; Cantor, 1997). Health considerations related to nitrate are actually the result of the conversion to nitrite in the stomach. Nitrite can then form numerous carcinogenic compounds upon reaction within the stomach. Work is currently underway to investigate the link between nitrate in drinking waters and early onset (childhood) diabetes.

Nitrate removal is not commonly available at works treating upland waters. The identification and minimisation of catchment area hazards is therefore particularly important.

In addition to nitrogen compounds, phosphates and potassium are also significant hazards related to agricultural activities. Algal blooms caused by increased nutrient levels can cause discoloration problems, may increase the cost of treatment activities and significantly reduce the amenity value of the source waters. If they contaminate drinking waters, the by-products from the breakdown of these blooms can cause taste and odour problems. The maximum levels for nitrates in both drinking water and water to be abstracted for potable supplies is 50mg l^{-1} (as NO_3), the same as the WHO guideline value. Nitrite levels must not exceed 0.1 mg l^{-1} in drinking water, although no value is stipulated for raw waters (WHO guideline 3 mg l^{-1}). Maximum permissible ammonia levels in water are 0.5 mg l^{-1} (drinking water) and 1.5 mg l^{-1} (DW2 raw waters). Neither phosphate or potassium standards are set for the quality of raw water abstracted for potable supplies, but PCV levels of 2000 mg l^{-1} (as phosphorus) and 12mg l^{-1} respectively, apply to treated waters.

Present knowledge of potential source areas

The general upward trend in UK nitrate levels has been correlated with the rise in agricultural intensification on numerous occasions. Nitrate fertiliser is the most widely used chemical supplement in farming (Gray, 1994) and thus runoff from agricultural land forms the primary source of nitrates in raw source waters. In addition to arable fertiliser use, nitrogenous fertilisers are also used on moorland areas to promote the more palatable grasses for upland sheep grazing. The ploughing of grasslands and spreading of manure may also increase nitrate and nutrient levels in upland waters. Animal wastes, whether deposited directly on the ground or spread as fertiliser are a significant potential source of nitrogen, phosphates and potassium compounds. Farming subsidies have also increased the number of animals grazing in upland areas, hence adding to the nutrient loads (Mitchell, 1991).

Building of Source tree and GIS data model

Figures 7.17 a) and b) show how digital data were collated and assessed to identify various hazard source areas for nitrate, phosphates and potassium compounds.

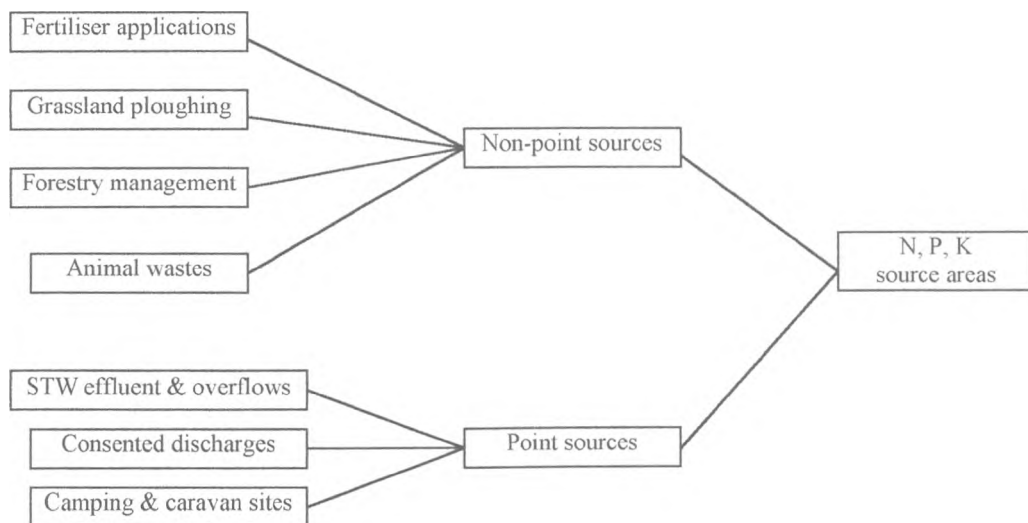
Nitrate hazard areas can be predicted by identifying those areas where nitrate fertiliser may be applied to agricultural land. The transport of nitrates by surface runoff will also increase the potential for surface water contamination. The coarse resolution agricultural census data were again used to identify the types of crops present in the catchment. Average fertiliser application rates were then determined for each crop type from the British Survey of Fertiliser Practice (HMSO, 1994). This enabled the relative contribution to nutrient enrichment of different crop types to be assessed and ranked on a five point scale. These areas were then sub-divided using the 25m resolution ITE Landcover data to identify areas within the 4 square kilometres where these crops will actually be.

Identifying source areas of animal waste, both deposition through grazing activities and deliberate spreading for fertiliser applications, was done as for cryptosporidium and faecal bacteria. Nutrient levels may also be increased by forestry activities (Mitchell, 1991), especially following pre-forestation ditching and clear felling. These were therefore identified by selecting all areas of bare ground from the ITE Landcover data that were surrounded by areas of managed forest. All non-point sources were then combined with the RPI to show which were most significant in terms of potential impact on surface water quality.

The extent of nitrate vulnerable zones (NVZs) and nitrate sensitive areas (NSAs), available as digital data from English Nature were also used to identify locations that were known to present a significant potential source of nitrate pollution.

Numerous potential point sources for these compounds also exist and were identified from the digital data. The primary potential sources are effluent discharges from sewage treatment works, combined sewer overflows and consented discharges. Caravan parks and camp sites were considered to represent a major hazard due to the high number of portable and chemical toilet facilities that may be used and emptied on or near the sites. Many of these features were present in the various data held within GISLAB, as illustrated in Figure 7.17 b), but further hazards were identified from the unique data layers created from paper records of discharge consents and from the OS maps using the automated and manual techniques described previously.

Figure 7.17 a) Nutrients Source Tree



Where areas of grassland ploughing and forestry management were identified, 5 points were added to the overall ranking total and 4 points were added if a cell fell within a Nitrate Sensitive Area (NSA) or Nitrate Vulnerable Zone (NVZ). (Although no such areas are officially identified in the Upper Wharfe and this weighting was therefore not used here, the NSA and NVZ variable has been incorporated in the Source Tree for completeness).

Figure 7.17 b) Nutrients GIS data model

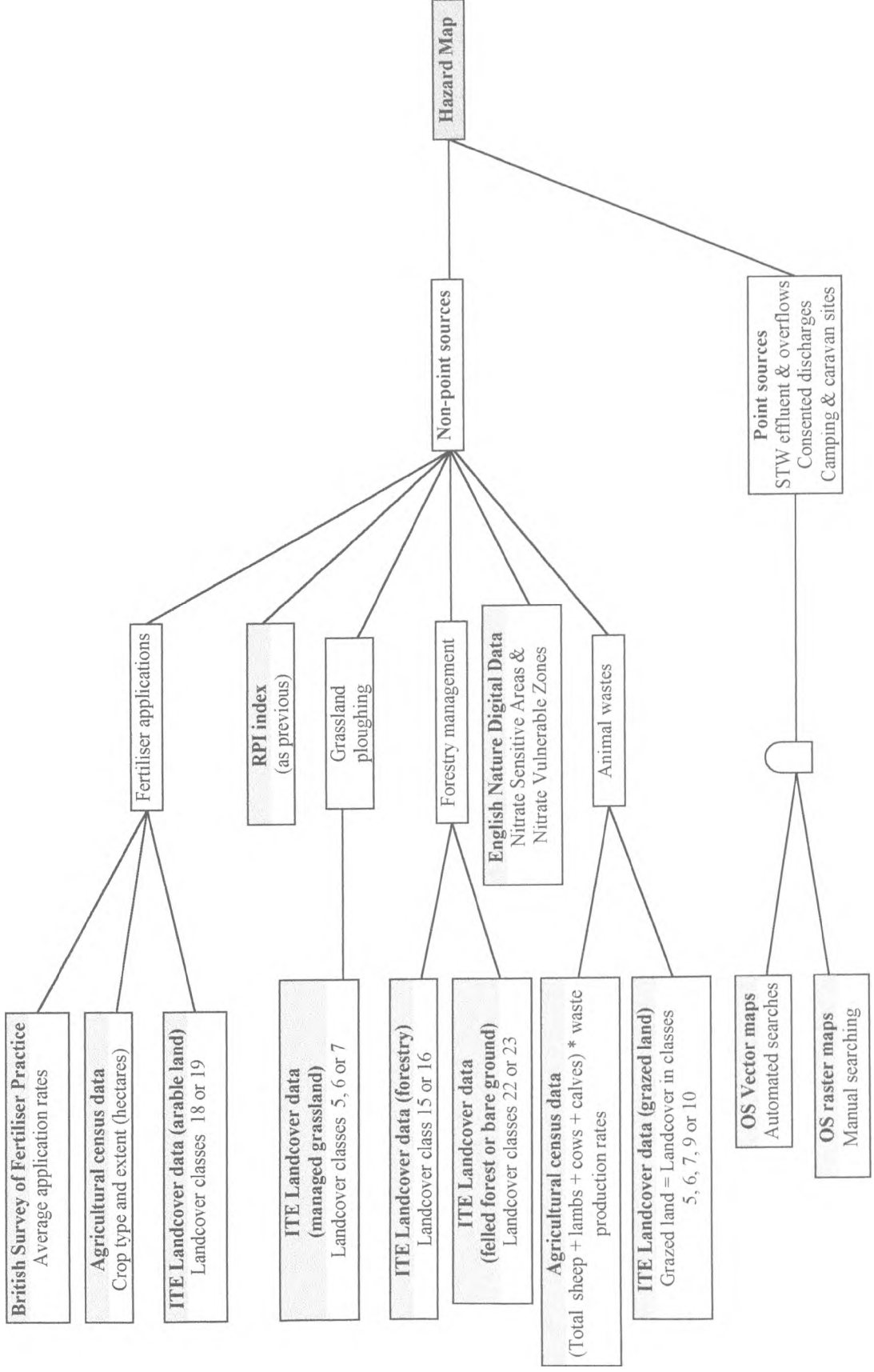
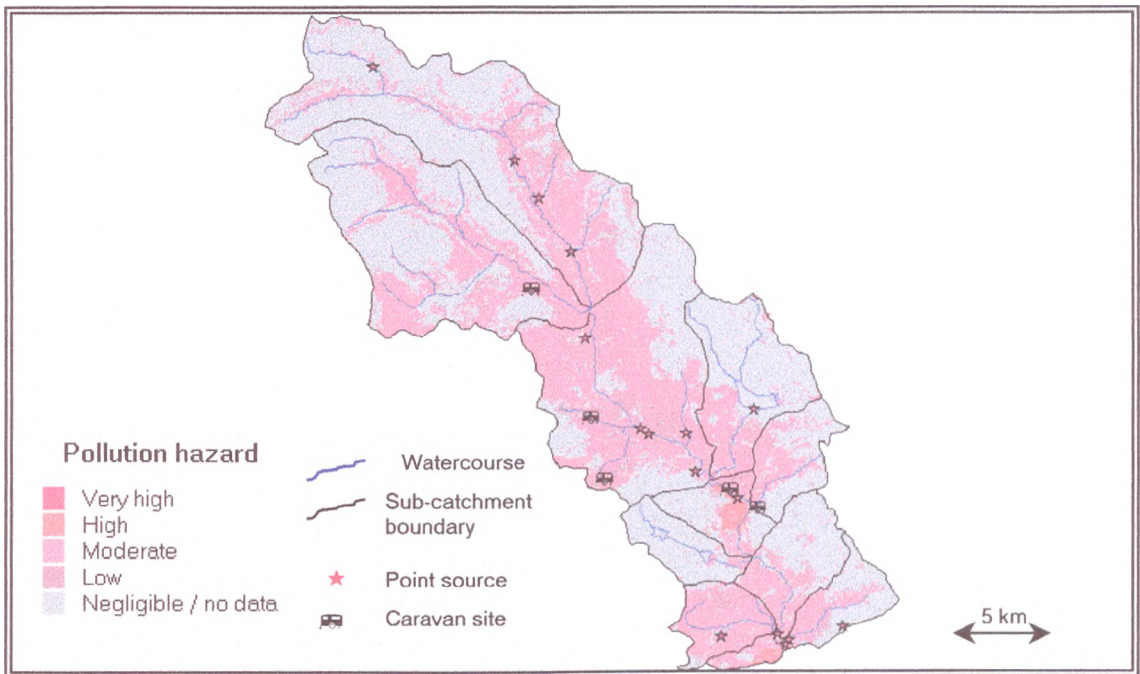


Figure 7.18 Nutrients hazard map



In general, the potential hazard areas appear to be from non-point sources where grazing land is in close proximity to the watercourse, e.g. throughout Langstrothdale and Main River 1. The Main River 1 and Halton sub-catchments are identified as the greatest hazard to water quality, whereas the Barden sub-catchment contains only a very small contributing area (moderate hazard) and no point sources. There are a large number of potential point sources in some of the other sub-catchments that may make a significant contribution to the nutrient load at the intake site. In particular the reach immediately upstream of the intake contains a number of potential sources, as does the Kex Beck sub-catchment.

7.2.10 Phenolic compounds

Introduction / background

Although phenolic compounds are not routinely monitored in the Upper Wharfe and were not therefore identified in previous chapters as a potential hazard, a number of phenolic pollution incidents have occurred in upland drinking water catchments throughout the UK and these substances are of particular concern to water supply companies (Foster & McDonald, 1996).

The term “phenolic compound” refers to any organic compound whose molecules contain one or more hydroxyl (OH) group bound directly to a carbon atom of a benzene ring. In their simplest form (phenol) the molecular structure contains 6 carbon and 5 hydrogen atoms bound in a ring, with an OH group directly attached to one of the carbon atoms (chemical formula: C_6H_5OH).

Any compound which contains this structure anywhere in its molecular form can be said to be a *phenolic*. The family of phenolic compounds, is therefore huge with a diverse range of properties and associated impacts on drinking water quality and the environment as a whole.

The primary significance of phenolics in drinking water is their ability to cause unsatisfactory tastes and odours at extremely low concentrations. Several phenolics have the ability to impart tastes and odours to drinking water supplies and edible aquatic life at parts per billion levels ($\mu\text{g l}^{-1}$) and have been shown to be toxic to aquatic life at parts per million levels (mg l^{-1}) (Buikema *et al*, 1979). The organoleptic properties of phenolic compounds have been the primary reason for stipulating such low compliance levels in drinking waters (EC MAC for total phenols = $0.5 \mu\text{g l}^{-1}$).

Phenolic compounds are also known to affect human health, and in some cases can be highly toxic. In high concentrations they can cause diarrhoea, nausea, vomiting, abdominal pains, mouth sores, dark urine and tissue burns in consumers ingesting contaminated water (Jarvis *et al*, 1985). High levels of phenolic compounds in freshwater can be mutagenic to *Escherichia coli* and toxic to microbes, algae, plants and animals (Buikema *et al*, 1979), and Milner & Goulder (1986) found that the activity of bacteria to be inhibited by increased levels of phenolic compounds.

If phenolic compounds are present in water during chlorination they can react with free chlorine atoms. Phenol itself has been found to be the most reactive aromatic towards chlorine incorporation during treatment (Buikema *et al*, 1979). Chlorophenols (which have taste and odour thresholds below the level of detection of laboratory methods) can therefore easily form if phenolic compounds are present in raw waters (Horth *et al*, 1992). These adverse taste and odours are often detected first by customers at the tap, resulting in complaints to the supply company. Phenolics therefore present an excellent example of where catchment control has the potential to reduce the contamination of drinking water supplies, due to lack of suitable monitoring technologies. Further detailed investigations into the monitoring of phenol in environmental waters can be found in Foster & McDonald (1996).

The precise phenolic compound causing taste and odour complaints is thought to vary between occurrences and is rarely identified (e.g. Horth *et al*, 1992). In the case of incidents in Yorkshire, phenol and para-cresol (4-methylphenol) have been detected in the upland waters at the time of customer complaints and thought to be the main precursors. The precise source and processes causing their mobilisation are unknown at present.

Present knowledge of potential source areas

Very little is currently known about the potential sources of phenolic compounds in upland water supply catchments. This has primarily been due to the lack of reliable monitoring equipment for environmental waters. However, some estimation of the potential source areas can be predicted. The occurrence of phenolics can be categorised into two sources. Synthetic compounds from anthropogenic activities and naturally occurring compounds in the environment. Synthetic phenols may come from road surfacing materials, wood preserving chemicals or effluent discharges. However, road surfacing materials are only thought to present a problem during the period of application (as it is the tar used that contains phenolic compounds), similarly wood preservatives present the greatest hazard when stored, prior to application.

The most likely sources of phenolics in upland catchments appear to be agriculture and the by-products of organic decay. Several phenolics are used as pesticides, or are present in pesticide compounds, especially 2,4-dichlorophenol and pentachlorophenol (Kruus *et al.*, 1991) and in the by-products of their decay (Buikema *et al.*, 1979). Sheep-dips are an acknowledged phenolic hazard in upland areas. Littlejohn (1987) and Littlejohn & Melvin (1991) found high concentrations of phenolics in the dipping solutions in use the Dee catchment in Scotland, and discovered hydrological pathways to local watercourses. However, they failed to find significant traces of the phenolics in local streams, illustrating the complex (and poorly understood) behaviour of these compounds.

Many incidents that have been traced to upland catchments are thought to originate from diffuse sources, and are therefore most likely to be from naturally occurring phenolics. Possible sources of naturally occurring phenolic compounds include animal waste products and decaying vegetation. Littlejohn & Melvin (1987) found significant amounts of phenolics in the effluent from dry and wet rotting grass under laboratory conditions and in silage effluents on farms. The amount produced varied greatly with the dry matter content of the silage. Rump (1974) isolated several phenolic acids from the urine of domestic farm animals, and cattle and pig slurry have subsequently been suggested as possible sources of phenolics (Littlejohn, 1994 - *Pers Comm.*).

Decaying vegetation can produce phenolic compounds. Rockwell & Larson (1978) identified leaf litter as the source of phenolics causing taste and odour problems whilst Ertel & Hedges (1984) found phenolics in the degradation of lignin substances from the decay of vascular plant material. Gordon (1990) found that the greatest amounts of phenol and para-cresol were formed from grasses with a high chlorophyll content. Small amounts of phenol were produced in by peat soils, but compounds such as para-cresol were not.

The above represents a summary of the limited current knowledge of phenolic compound source areas. The resultant hazard maps therefore represent a best guess scenario based on the current research base. As knowledge of phenolic compounds increases, so the hazard mapping can be refined and improved.

Building of Source Tree and GIS data model

Several potential point and non-point sources have been identified from the literature and previous fieldwork. These are represented in the Source Tree shown in Figure 7.19 a) below.

Figure 7.19 a) Phenolic compound source tree

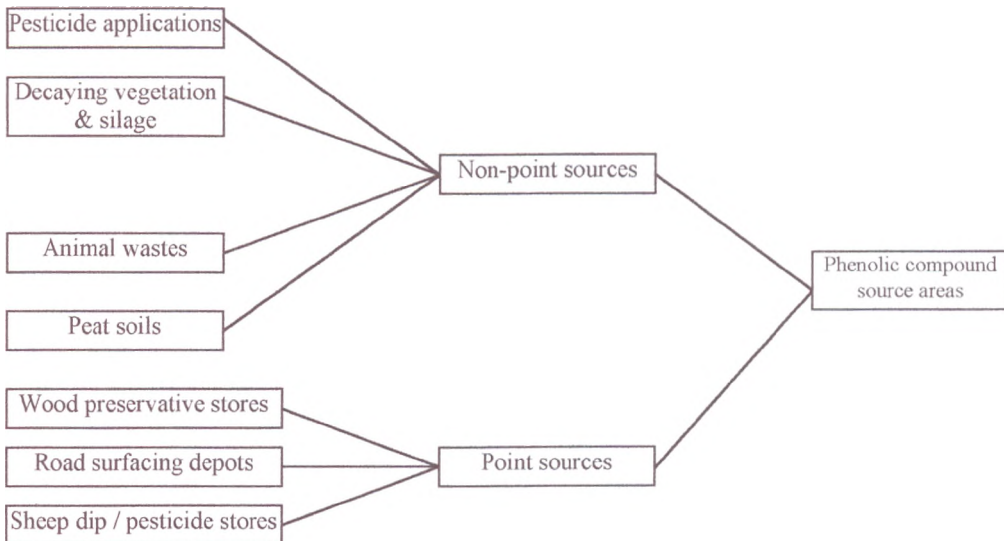
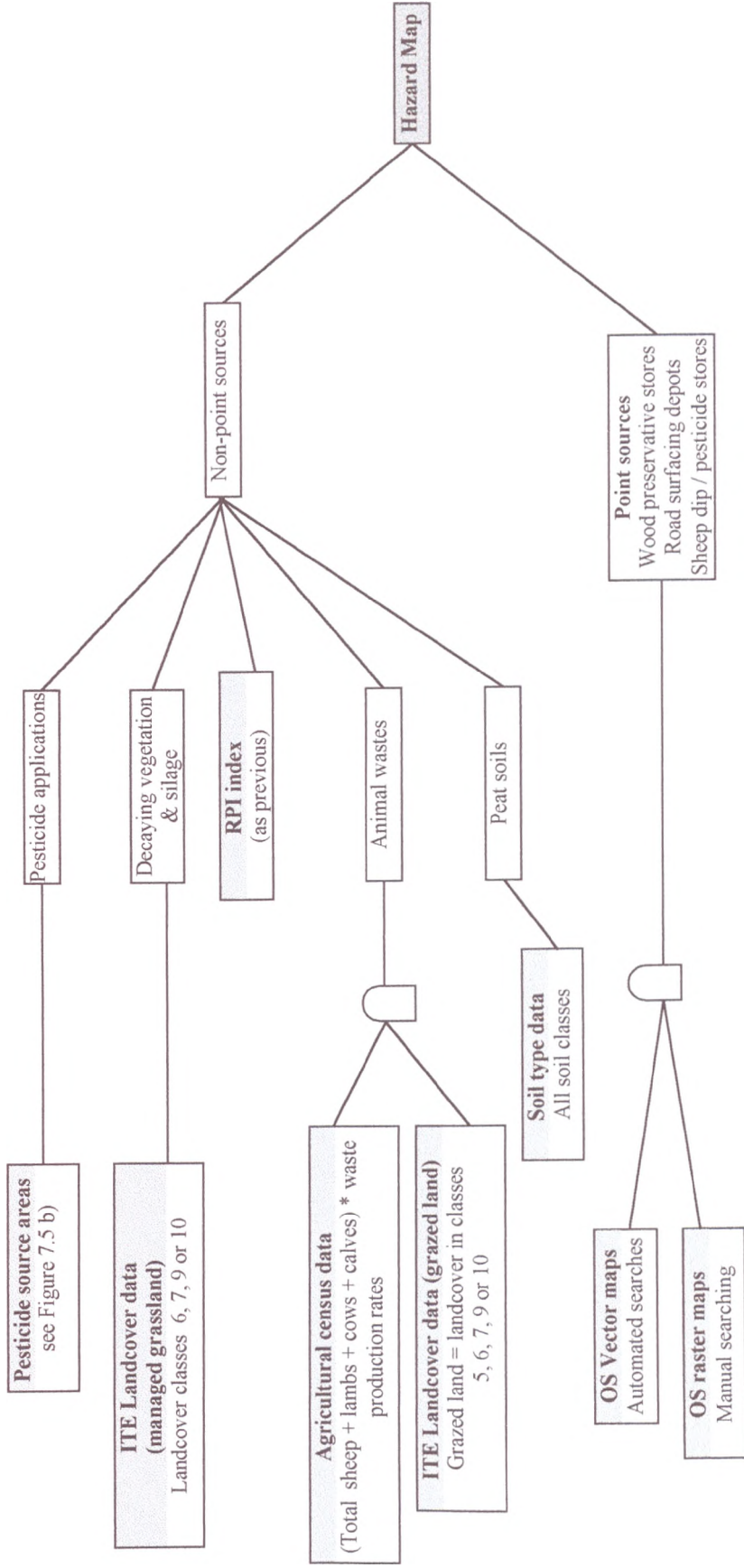


Figure 7.19 b) illustrates how these potential sources were identified in the GIS hazard mapping. Areas of pesticide application were identified as described in section 7.2.3, but only those areas where pesticides known to contain phenolic compounds may be applied were used on this occasion. Similarly, animal wastes and peat soils were identified as described previously from the agricultural census data, ITE Landcover data and waste production rates, and the soil series data respectively. All point sources were identified from automated and manual searches of the OS background maps. Sources associated with silage may be either point or non-point. They are represented only as non-point sources here as any potential silage storage areas will be highlighted when agricultural buildings are identified as part of the sheep dip and agricultural pesticide point source survey. Phenolic compounds may contaminate water where grass has been cut and left to ferment on land liable to experience overland flow. These areas were therefore identified using a combination of the ITE Landcover data (managed grassland) and the RPI index.

Figure 7.19 b) Phenolic compounds GIS data model



In order to represent the relative contribution of the different non-point sources of phenolics a weighting equation was applied to the ranking. As very little is known about the magnitude of phenolics from each source, this weighting is a simplistic one based on assumptions made from the limited research carried out in the field of non-point sources of phenolic compounds. The weightings applied are as follows:

Table 7.4 Modelling equation for phenolic compounds hazard map rankings

Modelling equation	
Total non-point source rank =	$(\text{Pesticide rank} * 5) + (\text{Decaying vegetation rank} * 4) + (\text{Animal waste rank} * 3) + (\text{Peat soil rank} * 2) + \text{RPI rank}$

Figure 7.20 Phenolic compounds hazard map

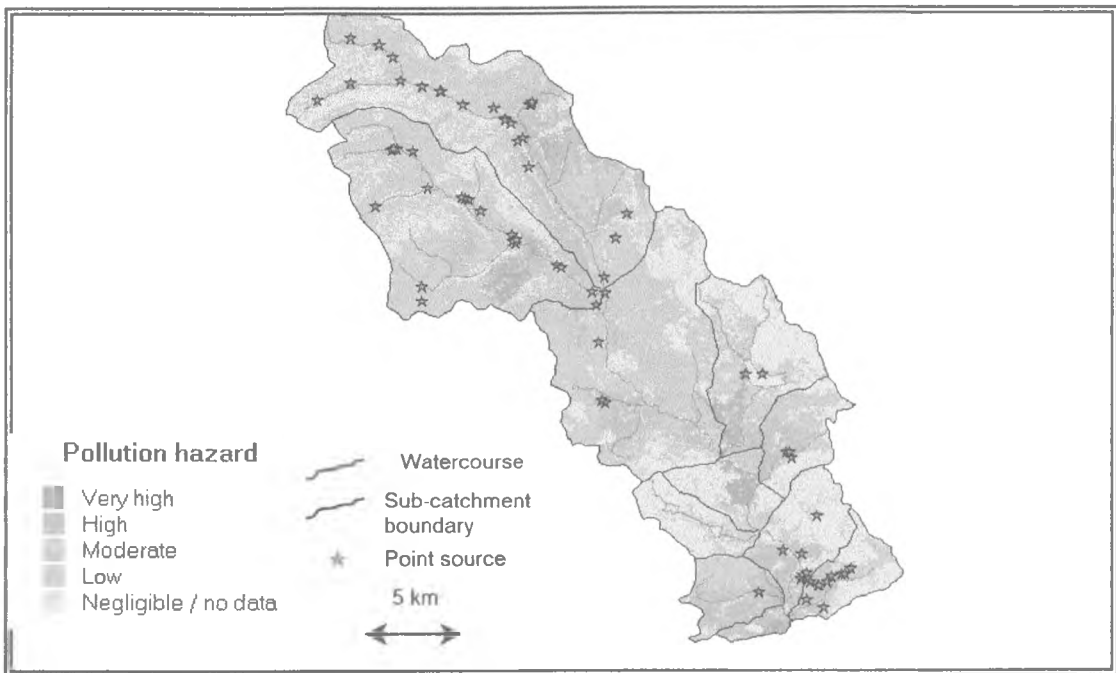


Figure 7.20 shows areas of high a very high risk in numerous sub-catchments. In particular, a large area of “Very high risk” land can be seen in Littondale sub-catchment and also in the Main River 2 sub-catchment. These represent areas with a high potential for pesticide application and/or decaying vegetation to be present that are on steeply sloping land or close to the watercourse (i.e. high RPI rank). In addition, a large number of potential point sources can be seen throughout the catchment, including several along the river in both Littondale and Langstrothdale, and a particular concentration in the Kex Beck sub-catchment. As mentioned previously with pesticide hazards, a high concentration of point sources as near to the intake site as Kex Beck represents a significant hazard to the quality of the water abstracted.

7.3 WINGS or MapInfo for GIS-based hazard identification? – The relative merits of two software packages

The need for two software packages came to light as much of the source data were made available through the WINGS-based GISLAB initiative at Yorkshire Water. However, the WINGS software package was known to have limited data manipulation capabilities, as the spatial analysis tools are still under development. MapInfo was therefore selected to carry out the spatial analysis as this represented the leading PC-based desktop GIS software at the time of the study.

Use was made of GIS in both chapters six and seven to facilitate the investigation of historical data. Much of this was simple on-screen representation of digital historical data. The storage of catchment information in this way has a number of advantages over paper mapping as the data can be automatically interrogated easily for use in a variety of ways, and can easily be updated when more timely information or scientific understanding becomes available. In general, such data can be displayed equally well in either software package, although the creation of original data layers (or maps) was often easier in MapInfo due to its simple tabular data structure and the ease of interaction with other packages such as Microsoft Excel.

The use of “Mifmerge” software that enables data transfer from MapInfo to the WINGS data format was a significant advantage. However, the reverse of this, when data were transformed from WINGS format for analysis in MapInfo was not totally automated and involved considerable manual conversion using alternative software such as text editors and spreadsheets. The text files associated with the WINGS data structure had to be manually converted into the correct format for import to MapInfo. Some of this was automated by the creation of text editing and data sorting macros in Microsoft Word and Excel, but considerable time was spent manually transforming and especially verifying the data. However, once these transformations had been carried out, interaction between the MapInfo-based GIS analysis and the WINGS-based desktop mapping “front end” was not computationally intensive due to the use of the Mifmerge software.

The limited spatial analysis tools available within WINGS meant that hazard maps could only initially be displayed as the largest spatial unit of the source data. This was because the cell-based data could not be dis-aggregated using higher resolution data as it could in MapInfo. Experimental (beta release) polygon algebra functions were tested within WINGS, but found to be inferior to the MapInfo overlay and analysis tools. The ability to select geographical areas contained within other spatial units in MapInfo enabled the larger resolution data to be refined and mapped, based on their relative attribute values or location. This significantly enhanced the mapping procedure and allows the potential for the identification of individual field sites for remedial action to alleviate pollution risk.

Whilst the display and interrogation of the resultant hazard maps has been possible in both WINGS and MapInfo, the data processing capabilities of MapInfo were found to be much more suitable for the analysis of digital data. The successful creation of new data layers through the combination of existing data was found only to be possible using MapInfo. For example, the 25m ITE Landcover data could be used to identify which part of the catchment animal were likely to be grazing. Using MapInfo's SQL selection tools, the cells could then be assigned animal grazing intensity ranks in accordance with the rank of the 2km agricultural census data cell that they were geographically within. In all such cases cell rankings were utilised so as not to misrepresent absolute values when combining data of different resolutions. This was seen as a suitable method of addressing many of the problems associated with approximating information from values transferred from data of several scales.

The table-based format of maps in MapInfo allowed the combination of the different data layers based on either attribute data or geographical location, thus allowing true GIS analysis to be carried out to create the hazard maps. WINGS proved to have virtually no spatial analysis capabilities, but was proficient at desktop mapping and the visual representation of data layers created by MapInfo. Data created in MapInfo could be easily returned to WINGS for display purposes. The resultant hazard maps can therefore potentially be displayed across the corporate-wide mapping system in use at Yorkshire Water Services Ltd. Despite significantly increasing the size of the stored data files, these can still be easily held on the desktop PC and would not necessitate the purchase of large network or storage servers (Foster & McDonald, 1998).

The automated searching of digital data to identify potential point sources of pollution did make extensive use of WINGS' capabilities. The Ordnance Survey Landline data were stored within WINGS in such a manner that text strings could be easily searched to identify features of interest using the WINGS "dump" feature. In addition, the 1:10,000 raster background maps were visually searched in WINGS for those areas where the larger scale vector maps were not available. This was also carried in WINGS to avoid the need for the large picture files containing the mapped information to be repeated in a format readable by MapInfo.

The work described in this chapter could therefore have been carried out purely in MapInfo, if all of the GISLAB data were successfully transformed. However, the need for results to be easily displayed via the WINGS-based GISLAB system necessitated the use of two GIS software packages. The was largely successful and enabled the unnecessary repetition of data to be avoided.

Future developments in GIS may well include the creation of OpenGIS specifications for the access of digital geographic data over networked systems (Anon., 1997). The use of multiple GIS software systems as illustrated by this work may therefore become more common in future years, although wide adoption of such approaches still remains unproven. This work has shown the potential of a multiple-GIS based system and illustrated its use on a medium specification desktop PC.

7.4 Summary and conclusions

This chapter has described the generation of hazard maps for a number of water quality parameters in the Upper Wharfe catchment. These have been created for parameters identified in the previous chapter and those known to cause problems to raw water supply quality in similar catchments. Hazard mapping of this variety is not evident in the contemporary literature but represents a significant potential application of environmental digital data. The digital mapping capabilities of the GIS have considerably improved the hazard identification process over those carried out in the past using inflexible data in paper format

Hazard maps were displayed using a five point ordinal ranking scale describing five levels of relative hazard from very high (5) to negligible / no data (1) for the following parameters: cryptosporidium, pesticides, oils and greases, colour, trace metals, faecal bacteria, lead, nutrients and phenolic compounds. It was possible to identify extensive areas of potentially highly hazardous conditions within the catchment, and to determine particularly high risk sub-catchments from the resultant maps.

The chapter has illustrated how existing knowledge of water quality parameters can be harnessed and utilised within a GIS to create an interactive management tool. The best available data have been used to identify the potential hazards to the quality of water at the intake site. This enables the classification of areas of the catchment that are a potentially high risk for particular parameters. Only once these areas have been identified can the relative contribution of the catchment areas be determined and realistic risk management strategies investigated. Such strategies are discussed in later chapters.

Hazard identification using GIS has primarily been done on a catchment scale, but as data are stored in geographically referenced tables, these were easily subdivided into sub-catchments. This enabled shorter computational processing times for analysing and drawing complex information and also has the potential for sub-catchment scale risk assessments to be easily completed. The resolution of the data and use of background Ordnance Survey maps enable areas of high risk to be clearly related to actual locations in the catchment. Such approaches could have significant potential uses for land management planning, local area plans, Environment Agency LEAPs and predictive modelling of environmental change scenarios.

One of the major challenges faced was the incorporation of a variety of data in terms of both quality and resolution. This has resulted in some hazard maps being dominated by certain data layers. For example the dominance of the coarser scale soil data can be seen when determining the runoff potential index for areas of relatively low slope angle (see Figure 7.2). Whilst such situations can be used to illustrate the locally dominant environmental parameter, or to represent the controlling factor in a variety of scenarios, the approximations inherent in the coarser data layers represent a potential source of error in the resultant hazard maps.

This work has highlighted a scale-based problem inherent in the use of environmental data of various resolutions and scales. This is perhaps one of the most significant challenges for the future exploitation of this approach to hazard identification. However, the stated aim of this research was to use generically available data in order to produce a methodology that can be transferred to other catchment areas. The techniques described here are considered to represent those best suited to the data available at the time of the research. If data resolution were standardised or improved, this would greatly facilitate future assessments of this nature.

Two GIS software packages have been utilised together here, each with individual strengths and weaknesses. The MapInfo software proved vital in the analysis of the raw data due to the ability to combine cells based on their geographic location and/or their associated attributes. In addition, the desktop mapping capabilities of WINGS combined with the innovation of GISLAB provides realistic potential for the output from a pollution risk 'expert system' to be made widely available within YWS. Much greater use was made of the MapInfo software, due to the superior data analysis tools available, although the display of the resultant hazard maps is equally good in either package as only basic desktop mapping capabilities are required for this. A summary of the strengths and weaknesses of the two software packages used has shown the potential of a multi-system approach. The use of both software packages to facilitate the wider use of the hazard mapping techniques developed here is discussed further in Foster & McDonald (1998).

As well as creating visual representations of the areas of hazard to water quality in the catchment, data from which the maps were built can be used to provide statistical information about the relative hazard of the sub-catchment areas for a particular water quality parameter. The following chapter makes further use of this capability to determine exactly what proportion of the high / medium / low risk areas exist within any one sub-catchment, enabling contributory factors for the various water quality parameters to be investigated further.

The hazard maps created in this chapter have been based largely on the findings of previous studies and knowledge of water quality sources. It is necessary to determine the validity of this approach in relation to the water quality of the study catchment. Investigations in the following chapter therefore describe the comparison of the hazard maps to raw water quality. Data collected are also compared to catchment characteristics determined using the GIS to obtain a greater understanding of the relative significance of catchment dependant variables on water quality. If a catchment specific methodology were required then any assumptions made in the creation of the initial hazard maps could be minimised for conditions in the Upper Wharfe catchment to provide optimal mapping of the potential hazards to water quality.

GIS techniques have been used in a novel area of application to greatly enhance the hazard identification stage of the RASCAL risk assessment methodology put forward in Chapter 5. It is anticipated that further application of GIS techniques will contribute to the following stages of the risk assessment methodology.

Chapter 8

Raw water sampling programme

8.1 Introduction

This chapter describes the collection and analysis of water quality data from the Upper Wharfe catchment. Samples were collected in order to validate the hazard maps, to assist in the preparation of descriptive relationships between water quality and catchment characteristics, and to provide input data for risk frequency estimates. Funding was secured from YWS to carry out an extensive sampling programme in the study area for these purposes.

The purpose of this chapter is therefore twofold. Firstly, the validity of the hazard maps created in previous chapters will be assessed by comparison to the sample results. Secondly, information gathered as part of this validation will be used to provide an increased understanding of the water quality within the Upper Wharfe catchments, and in particular about how the catchment water quality relates to the physical characteristics of the sub-catchment areas.

The sampling programme itself was established through a combination of GIS-based methods relating to the hazard maps presented previously. The next section therefore describes how sample site locations and analysis suites were determined using digital information on catchment characteristics. The following two sections of the chapter then go on to describe the contribution of the sample results to the development of the RASCAL risk assessment methodology. Individual sample results are given in Appendix C and detailed analysis of trends in water quality has been summarised in numerous reports elsewhere (Foster, 1996; 1997a; 1997b; 1997c). This chapter therefore focuses on how the water quality information is used to enhance the development of the risk assessment methodology.

8.2 Design and implementation of a raw water sampling programme using hazard identification techniques and GIS

8.2.1 Sample point locations

The catchment area was divided into smaller sub-catchments based around the major tributary streams as described previously. This division allows detailed hazard mapping exercises and spatial analysis of the physical characteristics to be carried out within each sub-catchment area and also facilitates the investigation of relationships between catchment characteristics and water quality. The hydrological boundaries of each sub-catchment were digitised into WINGS using the topographical information

from the Ordnance Survey 1:50,000 contour data. Eleven major sub-catchments were identified, with potential for further division into smaller regions as necessary.

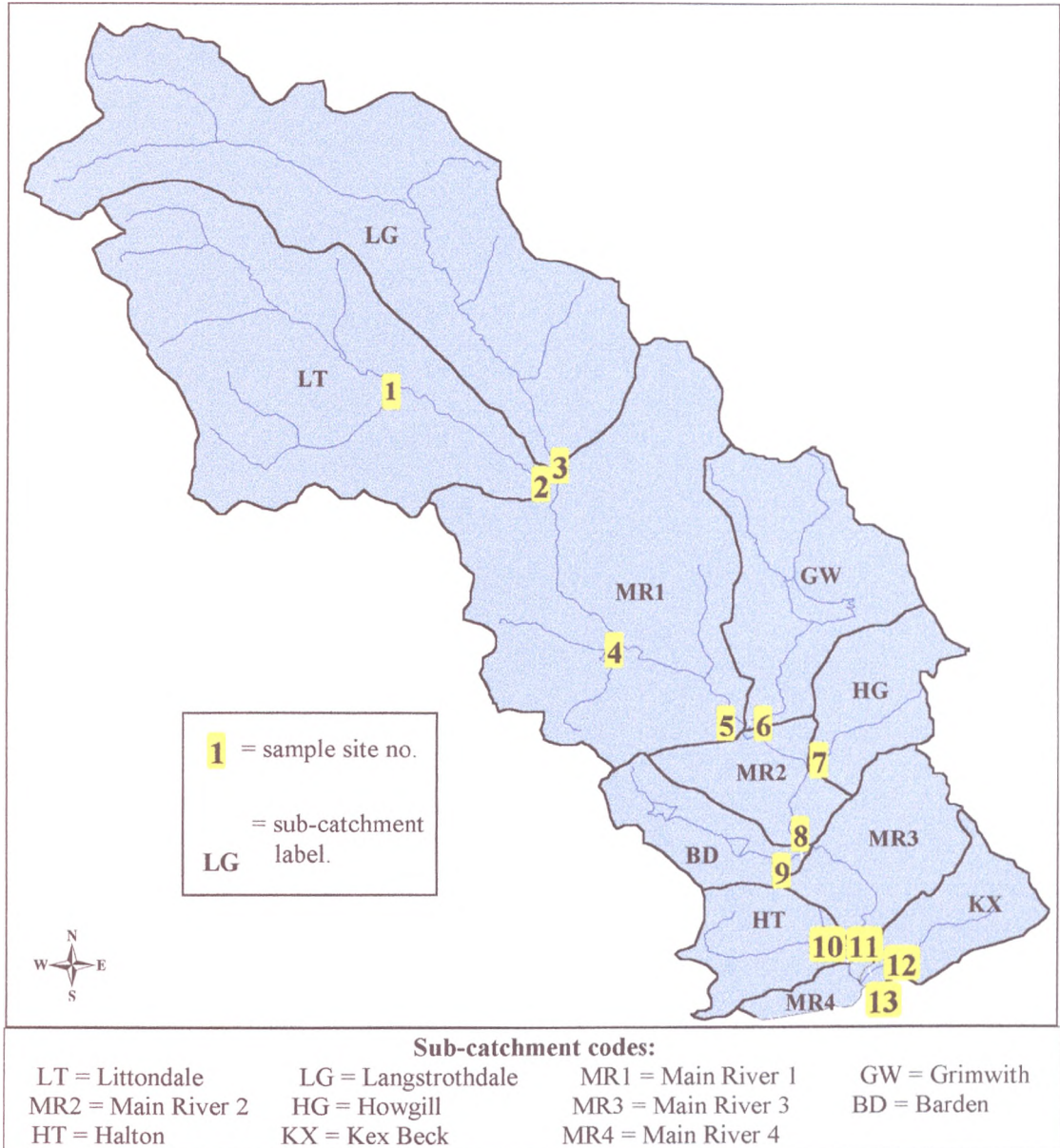
The physical characteristics of each sub-catchment have been investigated in the previous chapter to identify potential water quality hazards present. Recommendations for sample collection and analysis are made on the basis of these identified hazards.

The sample sites are located at the major outflows from each sub-catchment area, with additional sites on tributary streams that represent a significant potential hazard to water quality. These additional sites were located on Cowside Beck at Arncliffe (Site 1 in Figure 8.1), and Captain Beck at Linton (Site 4 in Figure 8.1). Cowside Beck was identified as being of particular concern due to the large number of animals located in the surrounding area and the high runoff potential of the steep-sided valley. Captain Beck was identified for additional sampling due to the location of Swinden Quarry in the upper reaches of this tributary.

The precise location of the 13 sample sites were identified by field visits, although preliminary site locations were detected by buffering the river link features in the GIS to highlight all reaches within fifty metres of a road, or where roads cross a watercourse. The sampling extended significantly beyond the existing monitoring carried out by YWS operational staff and the Environment Agency in the catchment and thus greatly increases the knowledge base of water quality information for the intake catchment and its associated sub-catchment areas.

The location of sub-catchment areas and sample sites can be seen in Figure 8.1 overleaf.

Figure 8.1 Upper Wharfe sub-catchment areas and sample sites



8.2.2 Sample analysis

The parameters measured at each site were determined by the upstream characteristics of the particular sub-catchment (or minor tributary). Four physical parameters were identified as standard measurements to carry out at each site. These were colour, turbidity, pH and conductivity. Analysis for nitrate, nitrite and several bacteria (total coliforms [TC], faecal coliforms [FC], faecal streptococci [FS], & Clostridia) also took place at all sites on a weekly basis. At some sites additional parameters have also been stipulated as a result of the hazards identified in particular sub-catchments. These include cryptosporidium, pesticides, phenolics, BOD₅ and a test for oils & greases. These are summarised in Table 8.1 overleaf. Samples were analysed by the ALcontrol laboratory in Bradford. The laboratory, approved by the United Kingdom Accreditation Service (UKAS), carries out chemical and microbiological analysis for YWS and commercial customers.

Table 8.1 Sample site locations, major hazards and sampling requirements

No	Location (Grid reference)	Major hazards identified	Parameters to monitor			
			Weekly	Fortnightly	Monthly	Other
1	Cowside Beck, Arncliffe Bridge (SD 930 719)	High runoff potential High animal density (<i>crypto., bacteria, nutrients</i>), Large areas of peat soils (<i>colour and trace metals</i>)	Physical – colour, pH, turbidity, conductivity. Metals – Al, Fe, Mn. Bacteria – TC, FC, FS, Clostridia Nitrates & Nitrites Ammonia-N		Cryptosporidium	
2	River Skirfare, Skirfare Bridge (SD 971 691)	High runoff potential Relatively high animal density (<i>bacteria, nutrients</i>) Large areas of peat soils (<i>colour and trace metals</i>) High number of sheep-dips (<i>phenolics & pesticides</i>) Caravan Site (<i>ammonia & bacteria</i>)		As site 1 + phenolics		Pesticides (Oct, Nov, Apr, May, Jun, Jul)
3	River Wharfe, Confluence with River Skirfare (SD 978 698)	Large areas of peat soils (<i>colour and trace metals</i>) Large area of coniferous (<i>colour, trace metals & nutrients</i>) 3 Sewage Treatment Works (<i>BOD, ammonia, bacteria</i>)		As site 1 + phenolics, BOD		Pesticides (Oct, Nov, Apr, May, Jun, Jul)
4	Captain Beck, Linton footbridge (SD 998 633)	High runoff potential Swinden Quarry (<i>fuel oils / diesel</i>) Rail depot (<i>fuel oils / diesel</i>)		As site 1 + oils & greases		
5	River Wharfe, Burnsall Bridge (SE 032 612)	Caravan site (<i>ammonia & bacteria</i>) 1 Sewage Treatment Works (<i>BOD₅</i>) Road junction near to river, road crossing at Burnsall Bridge (<i>oils & greases</i>)		As site 1 + BOD, oils & greases		
6	River Dobb, Hartlington (SE 040 609)	Large areas of peat soils (<i>colour and trace metals</i>) High number of sheep-dips (<i>phenolics & pesticides</i>)		As site 1 + phenolics		

Table 8.1 continued.

No	Location (Grid reference)	Major hazards identified	Parameters to monitor			
			Weekly	Fortnightly	Monthly	Other
7	Howgill Beck, Howgill (SE 060 593)	2 caravan sites (<i>Ammonia & bacteria</i>)	As site 1			
8	River Wharfe, Strid Wood (SE 063 565)	Sewage Treatment Works (<i>BOD, ammonia, bacteria</i>) Caravan site (<i>ammonia & bacteria</i>)	As site 1 + BOD			Pesticides (Oct, Nov, Apr, May, Jun, Jul)
9	Barden Beck, Strid Wood (SE 059 567)	Large areas of peat soils (> 70% of the sub-catchment) (<i>colour and trace metals</i>)	As site 1			
10	Haw Beck, Bolton Bridge (SE 070 529)	High runoff potential Major road (A59) (<i>oils & greases</i>)	As site 1 + oils & greases			
11	River Wharfe, Bolton Bridge (SE 071 527)	Major road (A59) (<i>oils & greases</i>)	As site 1 + oils & greases			
12	Kex Beck, Beansley (SE 078 524)	High runoff potential Major road (A59) (<i>oils & greases</i>) High animal density (<i>cryptosporidium, bacteria, nutrients</i>)	As site 1 + oils & greases		Cryptosporidium	
13	River Wharfe, Lobwood Intake (SE 075 519)	<i>All upstream hazards</i>	As site 1 + phenolics, BOD, oils & greases	Pesticides	Cryptosporidium	

NB. Pesticide monitoring was carried out at Site 8 as it represents the intermediate point on the mainstream River Wharfe.

In all, 3228 samples were collected and 15202 results determined from these by the laboratory. The results of the samples can be found in Appendix C and have also been reported in detail elsewhere (Foster, 1996; 1997a; 1997b; 1997c) including consideration of general water quality trends and the identification of anomalous results. Rather than repeat this reporting here, it is intended to describe examples of the utilisation of the sampling data to assist in the refinement of the risk assessment process. Namely, to determine the success of the hazard mapping approach and investigate relationships between sub-catchment characteristics and water quality. The water quality information is therefore used to determine the degree of success of the approaches developed in earlier chapters.

As the hazard maps developed earlier are based on generic assumptions of water quality relationships with geographical catchment characteristics, investigations are then carried out into relationships identified in the Wharfe catchment from these results. Such relationships can subsequently be used to improve the understanding of water quality hazards in the study catchment and hence refine the hazard mapping and risk assessment process in future iterations of the methodology. Thus allowing the fundamentally important feedback loop of continual re-assessment identified in the conceptualisation of the methodology (Chapter 5) to be completed. The data are also used in later chapters to assist in estimations of risk frequency.

8.3 Utilisation of sample results to aid the evolution of the RASCAL methodology

8.3.1 Hazard map validation

Graphical comparisons

In order to assess the success of the hazard mapping exercises in Chapter 7, data describing the distribution of hazard ranks were compared to the water quality information. Examples are given in the following graphs for several parameters whose potential non-point sources were identified using the hazard mapping techniques described previously. Only results from 9 of the 13 sub-catchments were used in this comparison as these represented geographically distinct catchment areas. The intermediate “Main River” sub-catchments were not used due to influence of upstream catchments on the water quality at their outlets. The whole catchment area (represented by the “Lobwood” data) was also considered in the analysis. Where parameters were not routinely monitored in some catchments (e.g. pesticides) due to excessive analysis costs or a low predicted hazard, only those sub-catchments where sampling was carried out are shown on the graphs.

The proportion of each sub-catchment categorised in each of the ranking classes were extracted from the mapped data in MapInfo and the results analysed in a spreadsheet software package (Microsoft Excel 97). Figures 8.2 a) and b) show water quality variations in relation to the predicted distribution of hazard in the various sub-catchment areas.

The graphs can be described as following. The stacked columns represent the total area of each sub-catchment, with the colouring indicating the relative proportions of these sub-catchments identified in each hazard class (red = very high, grey = negligible). The solid line plot (on the secondary Y axis) displays the maximum values seen for the water quality parameter in question and the dotted line represents mean values over the sampling period. Maximum values are used to represent the maximum potential hazard of a sub-catchment witnessed during the sample period, whilst overall outputs from the sub-catchments are illustrated by the mean values.

Thus, if the hazard map predictions are correct then those columns with a greater proportion of red and orange colouring (very high and high risk areas) will correspond to the greatest maximum and mean water quality values shown by the line plots. This is illustrated well in Figures 8.2 a) and b) showing the colour and aluminium results. In the Grimwith sub-catchment, the high proportion of land classified as “Very high” (43%) colour hazard potential and “High” (37%) coincides with a significantly higher mean and maximum colour level compared to other sites. Similarly in Figure 8.2 b) sub-catchments with large proportions of the area classed as moderately hazardous and above have corresponding higher maximum and mean aluminium levels at the sub-catchment outlet sample points.

Figure 8.2 a) Distribution of Colour hazard and observed values

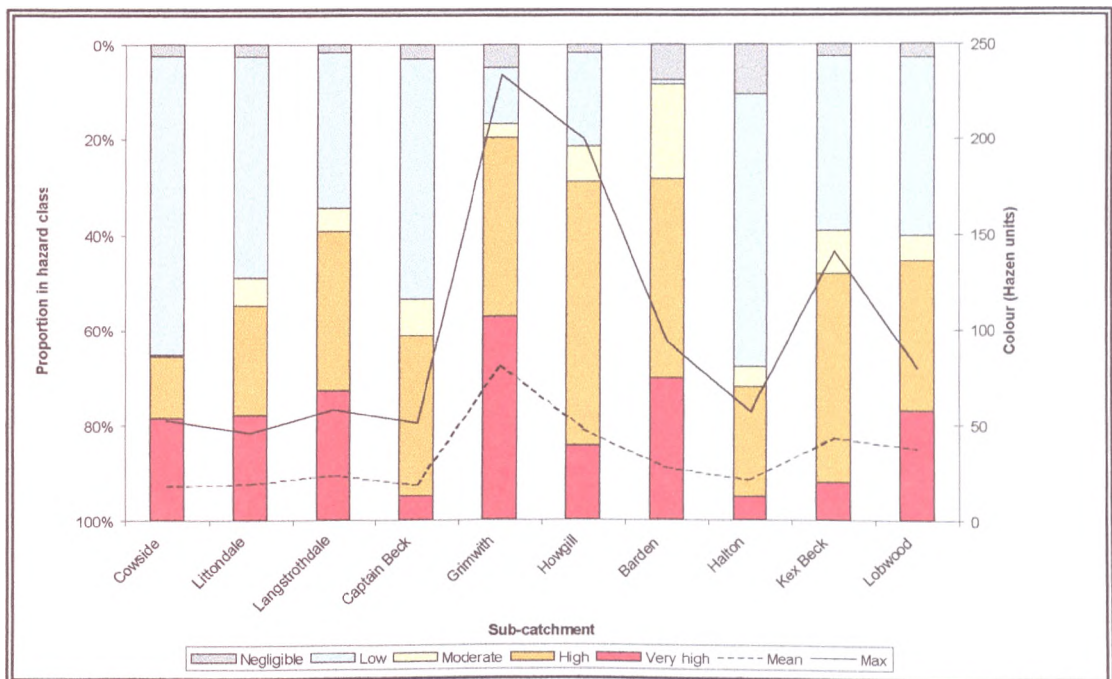
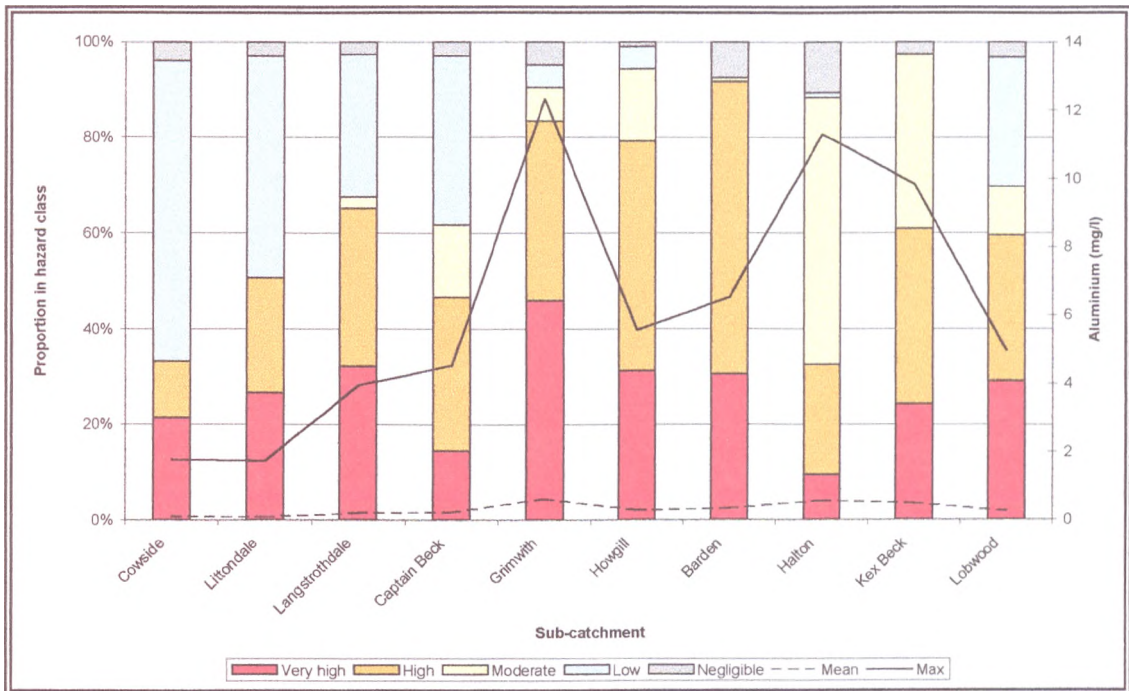


Figure 8.2 b) Distribution of Aluminium hazard and observed values

The general trend indicated by the graphs is that where more of the sub-catchments are classified in the higher rank categories, high maximum values are witnessed together with an elevated mean value for the sampling period as a whole. As such, the above figures indicate that the assumptions, weightings and data aggregation processes adopted in the source trees are broadly correct for colour and aluminium. For several parameters, insufficient water quality data are available to carry out meaningful statistical analysis. This is due to samples not being collected from all sites for particular parameters, or a high proportion of results being below the limit of detection for numerous parameters. The overall performance of the hazard identification predictions for these parameters is therefore shown by further graphical analysis in Figures 8.3 a) to 8.3 d) below.

The distribution of total pesticides seen in Figure 8.3 a) is of limited value as the prohibitively high analysis cost meant that pesticides could only be sporadically monitored at a selection of sites. However, where pesticides were detected (these were generally insecticides such as Aldrin and Protham) there was a limited relationship to the predicted non-point source hazards. In Littondale where the highest concentrations of total pesticides were seen (0.09 and $0.10 \mu\text{g/l}^{-1}$) there is the lowest proportion of Rank 1 ("Negligible") land area. However, in the other catchments monitored for pesticides no increase in pesticide concentration was seen with the increased areas of "Very high", "High" and "Moderate" risk areas. This may either be due to impact of point sources in Littondale, (which may be the case as pesticides were only detected on two occasions), or that no pesticide compounds were used, spilt, or sprayed during or prior to the sampling visits.

Figure 8.3 a) Distribution of total pesticides hazard and observed values

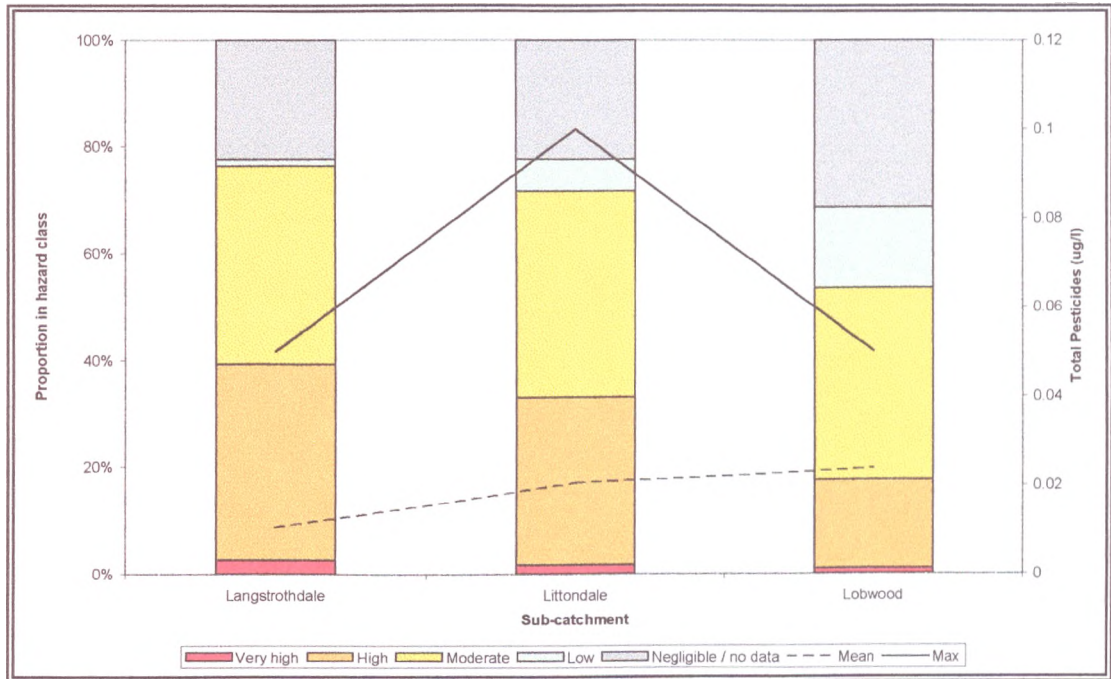
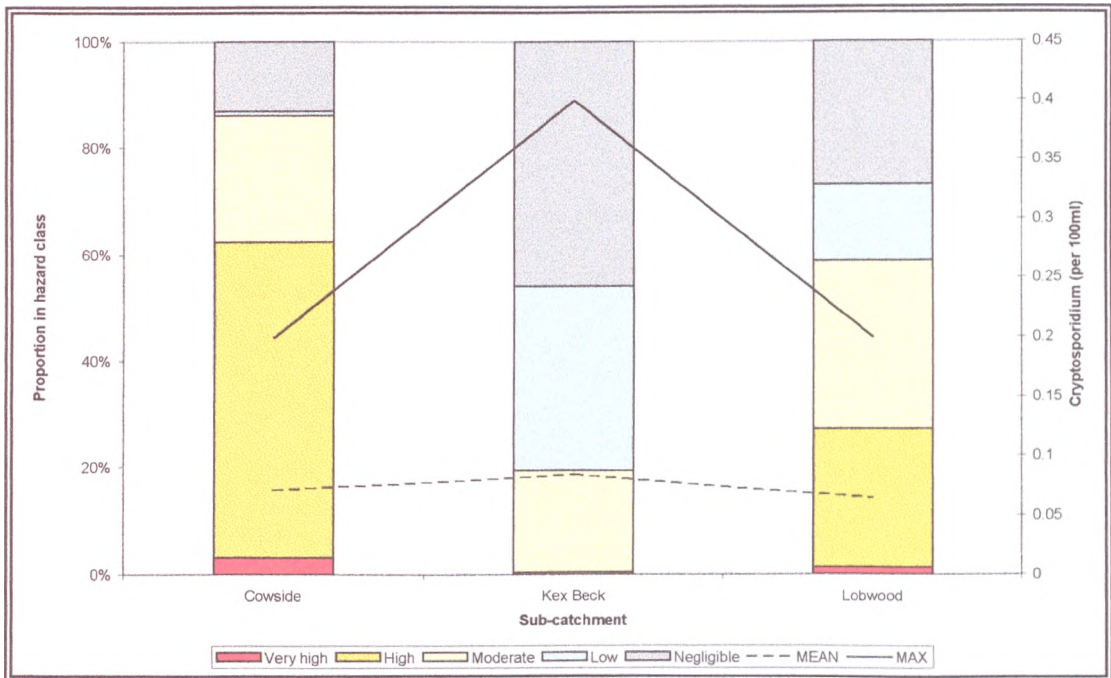


Figure 8.3 b) Distribution of cryptosporidium hazard and observed values

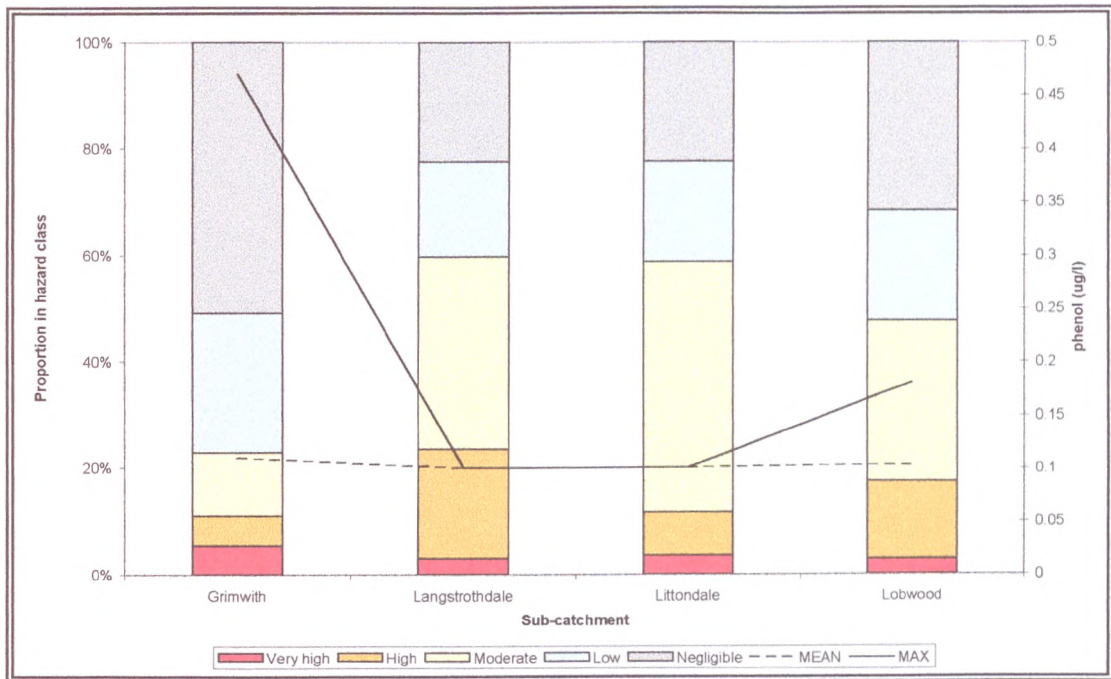


Cryptosporidium sample results are inherently difficult to analyse over time series as they are effectively a measure of presence or absence due to the limited accuracy of current methodologies (Marshall, 1997). Cryptosporidium oocysts were detected on only one occasion, in a sample from Kex Beck (Site 12). The hazard mapping in the previous chapter suggested this sub-catchment was potentially hazardous due to the high number of point sources in the catchment.

The positive cryptosporidium result was obtained during heavy rainfall and was seen in conjunction with high turbidity and coliform results. This therefore indicates that surface runoff from a faecal-contaminated area is likely to be the source of the oocysts. In this case therefore, the dominant transport process appears to be overland flow, as predicted for the main river by Marshall (1997).

Phenol and *p*-cresol (4-methylcresol) are parameters known to have caused problems before in similar catchment areas (Foster & McDonald, 1996) and were the only phenolic compounds detected during this sampling.

Figure 8.3 c) Distribution of phenol hazard and observed values



Phenol was detected in a sample from Littondale at a concentration of $0.47 \mu\text{g l}^{-1}$ and on two occasions at the Lobwood intake site (at concentrations of $0.13 \mu\text{g l}^{-1}$ and $0.18 \mu\text{g l}^{-1}$). These concentrations are considered high enough to produce taste and odour problems if present in the intake water. Little is known about the actual sources of phenolic compounds and three positive results here is not enough to identify trends or definitive sources. However, as no pesticides were detected at any of the sites on these dates it is likely that that sheep dip solution was probably not the source of this phenol. Potential sources are therefore likely to be related to the breakdown of organic matter in the catchment. Large areas of forestry in Littondale would provide an ample source of such material.

In contrast to the incidents of phenol witnessed, para-cresol (Figure 8.3d)) was detected in Langstrothdale in January 1997. Again no pesticide contamination was seen around this time. However, slurry spreading activities were seen taking place in the Langstrothdale sub-catchment area and high levels of bacteria found in results from the same day. It is therefore hypothesised that the source of the para-cresol is animal urine as suggested by Rump (1974) and Littlejohn (1994 – *Pers comm*).

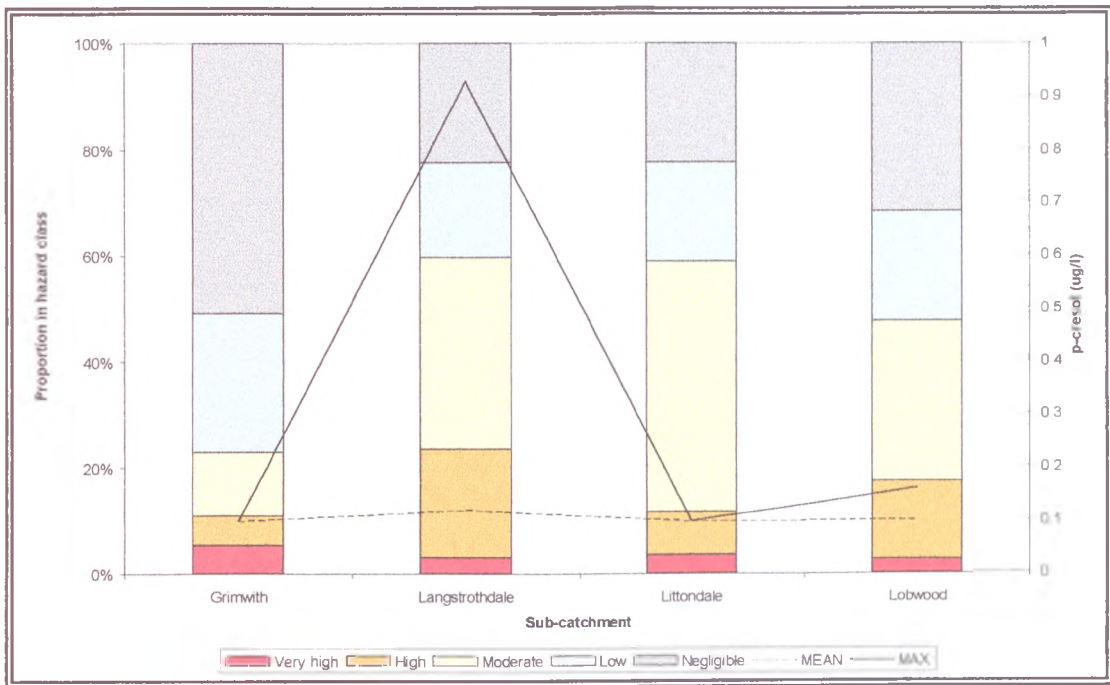
Figure 8.3 d) Distribution of *para*-cresol hazard and observed values

Figure 8.3 e) Distribution of Oils & Greases hazard and observed values

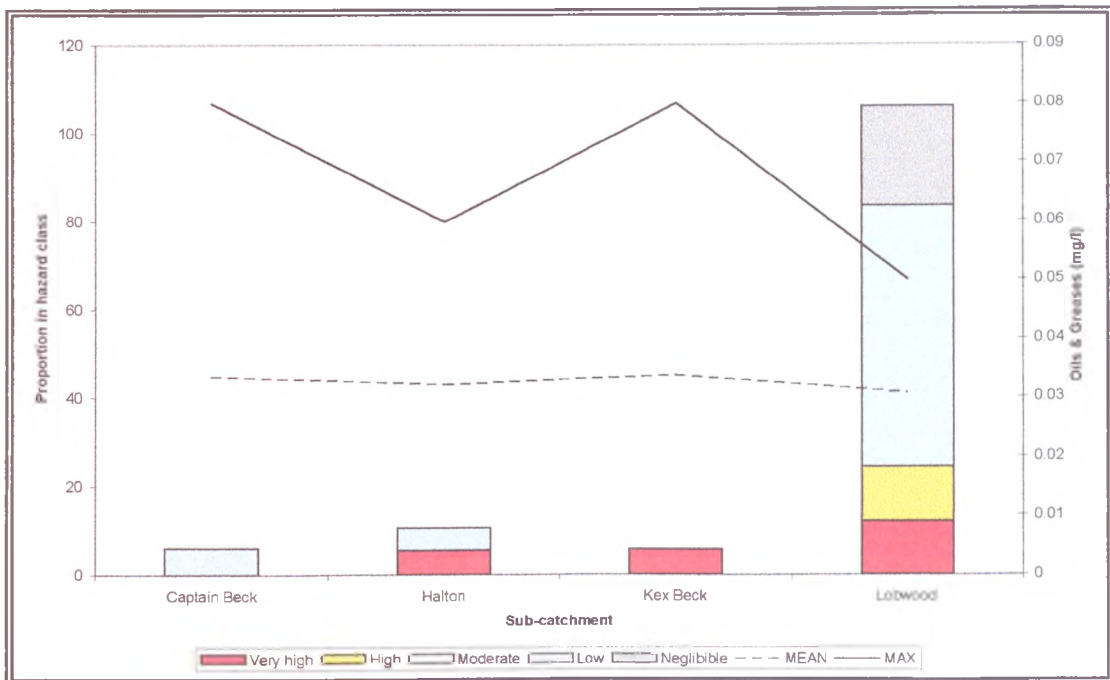


Figure 8.3 a) shows the proportion of roads in each sub-catchment in each of the hazard classes where oils and grease monitoring was carried out (oils and greases were also monitored at several intermediate points on the main river). The Halton and Kex Beck catchments were identified as a major hazard as the main A59 and A65 roads run adjacent to the streams in these areas. Captain Beck was identified as a potential hazard due to the location of Swinden Quarry in the upper reaches.

Few samples contained oil and greases above the limit of detection, with the highest values (0.08 mg l^{-1}) found in Captain Beck and Kex Beck. On 30/10/96 oil and grease were detected at Captain Beck, Kex Beck and several of the intermediate sample points. This was following several days of relatively intense rainfall and was associated with extremely high coliform counts at all sites. Turbidity levels at this time were not unusually high, so it is thought that the oil and grease may come from surface drains from the roads, or the overflow of storm tanks. Again however, the source of the contamination is unknown, although it was those sub-catchments with the highest predicted hazard potential that produced the high sample results.

Where sufficient information is available from the sampling programme, statistical correlation was used to assess the predictive power of the hazard identification mapping exercises.

Pearson correlation analysis

Pearson product-moment correlation values were determined for comparisons of observed sample results with the proportion of catchment classified into the five rank classes. Pearson correlation analysis can be used to measure the relationship between two data sets that are scaled to be independent of the unit of measurement. The calculation returns the covariance of two data sets divided by the product of their standard deviations. The analysis therefore determines whether two ranges of data move together.

Correlation coefficients were calculated for the mean, minimum and maximum values experienced at the outlet of each sub-catchment and related to the proportion of sub-catchment area in each hazard class and the number of point sources identified in the hazard mapping activities. The results are shown in Table 8.2 overleaf. For each water quality parameter, the sub-catchment proportion against which it is correlated is that calculated from the GIS for the parameter under consideration.

A statistically significant ($p = 0.05$) positive relationship is evident between the percentage of catchments classed as high colour hazard and the maximum colour levels seen at the sub-catchment outlets. Strong negative relationships also exist between %Low and both the mean and maximum observed colour.

Very few areas were categorised as “Very high” or “High” in the nutrient hazard maps that predicted possible sources of nitrate and nitrite hazard. The correlation coefficients for these will therefore be skewed somewhat by a lack of data (% Very High variable = 0 in many cases). However, significant positive relationships exist between %Moderate and maximum observed values. In addition a strong negative relationship ($p=0.01$) exists between %Negligible and the mean and maximum observed values for both nitrate and nitrite. The hazard maps therefore predict nitrate and nitrite levels well for the study sub-catchments.

**Table 8.2 Pearson product-moment correlation coefficients for water quality variables
v proportion of sub-catchment in each hazard rank**
($p = 0.05$; $p = 0.01$)

Parameter	Sample results	% Negligible	% Low	% Moderate	% High	% Very high	N° point sources
Colour	Min	-0.074	0.025	0.150	0.247	-0.335	-
	Mean	-0.053	-0.610	-0.094	0.525	0.538	-
	Max	-0.088	-0.656	0.033	0.693	0.400	-
Aluminium	Min	0.123	-0.411	-0.111	0.045	0.677	-
	Mean	0.589	-0.313	-0.122	0.181	0.179	-
	Max	0.589	-0.313	-0.122	0.181	0.179	-
Manganese	Min	0.411	-0.763	-	0.503	0.643	-
	Mean	0.435	-0.557	-	0.312	0.505	-
	Max	0.671	-0.261	-	0.264	0.055	-
Iron	Min	-0.130	-0.057	-0.274	0.165	0.438	-
	Mean	0.245	-0.729	0.420	0.296	0.386	-
	Max	0.716	-0.706	0.893	0.152	-0.460	-
Bacteria (Total coliforms)	Min	0.038	-0.682	0.236	0.980	0.133	-0.145
	Mean	0.051	-0.631	0.310	0.623	0.395	-0.092
	Max	0.097	-0.618	0.284	0.544	0.362	-0.194
Bacteria (Faecal coliforms)	Min	-0.075	-0.603	0.338	0.809	0.207	-0.165
	Mean	0.220	-0.667	0.157	0.678	0.344	-0.261
	Max	0.250	-0.660	0.118	0.681	0.336	-0.301
Bacteria (Faecal streptococci)	Min	-0.377	0.228	0.161	-0.030	0.213	0.656
	Mean	0.043	-0.626	0.492	0.183	0.080	-0.247
	Max	0.078	-0.627	0.509	0.059	-0.013	-0.269
Nitrate	Min	-0.639	0.611	0.611	0.117	0.555	-0.010
	Mean	-0.832	0.775	0.801	0.113	0.205	-0.038
	Max	-0.832	0.775	0.801	0.113	0.205	-0.038
Nitrite	Min	-0.702	0.616	0.685	0.033	-0.052	-0.134
	Mean	-0.802	0.767	0.768	0.036	0.175	-0.106
	Max	-0.737	0.647	0.719	0.057	0.141	-0.127

The coefficients calculated for aluminium and manganese are not so encouraging as significant relationships are evident between maximum water quality values and the %Negligible variable in both cases. In addition, positive relationships exist between %Very High and minimum metal levels. The format and weightings applied to the source trees in these cases therefore need to be reviewed for the Upper Wharfe sub-catchments. The Pearson coefficients for iron are more encouraging with %Moderate strongly correlated to mean and maximum values, and %Low negatively correlated to maximum values.

At first glance, the relationship between bacteria levels and the predicted source areas appear poor. However, the relatively small set of variables used here (only min, max and mean values) will be affected by the numerous “spikes” in bacteria levels observed at several sites.

In summary, Table 8.2 shows that for parameters where the sources and transport mechanisms are well understood (e.g. nitrates and colour) the source trees and GIS data models used to predict hazard areas are an accurate representation of observed values in the Upper Wharfe catchment during the sampling period. The relationships indicated by the preliminary plots shown in Figure 8.2 a) and b) have been shown to be statistically significant for colour, nitrate and nitrite levels. The prediction of the major contributing sub-catchments for iron was also good.

For several of the parameters considered, there was no significant relationship between the proportion of source area within a hazard class and the observed values at sub-catchment outlets. However, this may be due to the fact that results are only available for spot samples taken on 38 occasions during a 10 month period and therefore general trends and extreme events may have been missed by the sampling. For those parameters where correlation coefficients were not calculated due to insufficient, zero or disparate sample results, general relationships between the mapped predictions and sample results can be illustrated by graphical representation of the data.

The results may also have been skewed by poor performing catchments that under or over predicted the effect of non-point sources, or where point sources had extreme effects on sample results. For many parameters, such as oil, pesticides and cryptosporidium, there are no background trend levels evident on which to base predictions. For these parameters, the fact that a positive (or above the limit of detection) result was obtained from a sub-catchment identified as a possible source is an indication of the success of the hazard identification process.

The identification of source areas for all parameters was deliberately based on generic principles and an understanding of potential sources and transport mechanisms in numerous similar catchments. The water quality of the sub-catchments of the Upper Wharfe may therefore be influenced by additional factors not accounted for in the original hazard identification process.

In order to improve the prediction of hazard potential for future iteration of a risk assessment applied to this particular catchment area a better understanding of the relationship between catchment characteristics and water quality for the Upper Wharfe is required.

8.3.2 Example catchment characteristics / water quality relationships in the Upper Wharfe sub-catchments

As discussed above, for more accurate hazard identification predictions to be applied to the Upper Wharfe sub-catchments then the relationships between catchment characteristics and water quality need to be investigated further. This section shows some examples of relationships that can be identified from the observed sample data. The increased understanding of upland processes identified from these can therefore be incorporated into future generic risk assessments, or ones specific to the Upper Wharfe.

Mean and maximum water quality values were related to catchment characteristics using a stepwise multiple regression technique. The independent variables consisted of several values describing the morphometry of the catchment, land use type and animal populations. The morphometric variables were calculated in the GIS using the same definitions as those given by Mitchell & McDonald (1995). The thirteen variables used are summarised in Table 8.3 below.

Table 8.3 Independent variables used in regression analysis

Variable	Units	Definition
Basin area	km ²	Area of catchment or sub-catchment
Main channel length	km	Length of highest order stream
Total channel length	km	Total length of all channels (from Institute of Hydrology 1:50,000 digitised data)
Drainage density	-	Total channel length / Basin area
% peat in catchment	-	Percentage of catchment classified as peat soil (SSLRC class 10)
Relief ratio	-	Basin relief (max elevation – min elevation) / basin length (distance from mouth to farthest perimeter)
Area slope <5°	km ²	Area of slopes less than 5 degrees
Area of south (S) facing slopes	km ²	Area of slopes with aspect of 135° – 225°
% Forestry	-	Percentage of land area in ITE Class 16 (coniferous), 15 (deciduous) or 23 (felled)
% Arable	-	Percentage of land area in ITE Class 18 (tilled)
% Pasture	-	Percentage of land area in ITE Class 7 (meadow/verge/semi-natural), 6 (mown/grazed turf), 8 (rough/marsh grass), 5 (grass heath), 9 (moorland grass).
% Moorland	-	Percentage of land area in ITE Class 10 (open shrub moor), 11 (dense shrub moor), 13 (dense shrub heath), 25 (open shrub heath).
No. Animals	-	Total number of farm animals identified from the Agricultural Census Data

These independent variables were correlated to ensure that problems of co-linearity within the resultant regression equations were minimised. Table 8.4 shows three examples of the resultant regression equations that were determined for the Upper Wharfe sub-catchments, together with their respective r^2 values.

Table 8.4 Example regression equations for the Upper Wharfe sub-catchments

r^2 value	Equation
0.768	Mean Nitrate = $0.303(\% \text{arable}) - 0.054(\% \text{peat}) + 6.233(\text{Drainage density}) - 0.015(\% \text{moorland}) - 0.255$
0.800	Mean Colour = $3.812(\text{area} < 5^\circ) + 0.775(\% \text{peat}) - 1.706(\text{area S facing slopes}) + 0.122(\% \text{moorland}) + 9.589$
0.512	Maximum Bacteria [FC] = $7.831(\text{No. animals}) - 1924.926(\text{basin area}) + 11510.119$

As mentioned earlier these equations require too much site specific data to be used directly in the hazard identification stage of a generic risk assessment methodology such as the one being developed here. However, the identification of general relationships from these can be used to build the source trees, as was done in earlier chapters using work by previous authors (e.g. Boon *et al*, 1988; Mitchell & McDonald, 1995). As such, further work could be carried out using the water quality data collected from this sampling in order to provide additional knowledge about potential sources of water quality variations. This could then be incorporated in future amendments to the creation of source trees and GIS data models for hazard identification.

8.4 Conclusions

This chapter has described the development of an extensive water quality sampling programme on the basis of the hazard identification techniques developed in earlier chapters. GIS techniques were used in the development of the programme and the water quality parameters of interest identified from catchment hazard maps. The data from the sample results were then used to assess the performance of the hazard mapping predictions. The proportions of sub-catchment areas in each hazard class were compared to the sample results for the outlet of each distinct sub-catchment.

In general, higher levels of potential contaminants were detected in catchments with higher proportions of land classified as "Moderate" hazard or above. This relationship was evident from graphical representations of the distribution of hazard class and water quality results. However, statistical analysis of the same data indicated that this relationship was only statistically significant for colour, nitrate and nitrite predictions. Iron sources were also predicted with some success. It is concluded that the greater understanding of the processes controlling the source and mobilisation of these phenomena has led to the creation of more accurate source tree and GIS data models in the initial stages of hazard identification.

For several parameters, the fact that a positive (or above the limit of detection) result was obtained from a sub-catchment identified as containing potential source areas indicates the success of the hazard identification process.

The data obtained from the sampling can be used to identify relationships between water quality and the sub-catchment characteristics of the Upper Wharfe. Some preliminary investigations into this have been carried out and equations developed to predict water quality variations between the sub-catchment areas. These equations described 76.8%, 80.0% and 51.2% of variance in mean nitrate concentrations, mean colour and maximum levels of faecal coliforms respectively.

In general these represent good models when compared to the contemporary literature such as McDonald & Naden (1987), Boon *et al* (1988) and Mitchell & McDonald (1995). These relationships could also be used as the basis for improved hazard modelling in the future. The relationships identified for the Wharfe could be incorporated into the source trees and GIS data models in order to identify more accurate estimates of potential hazard location. Such an approach can be continually improved as more data are collected and processes are understood more clearly. The sample results analysed here have highlighted the need for a detailed understanding of the factors influencing water quality to be incorporated into the initial hazard identification stage, although not necessarily the use of vast quantities of historical data.

The catchment-specific water quality data collected in this sampling programme can therefore be continually fed back into the risk assessment process to improve the accuracy of predictions. In the development of a more generic approach, the data also has the potential to improve the process knowledge summarised in the source trees and GIS data models, as illustrated by the example equations presented here

The statistical analysis of the sample data presented here does not show strong relationships between the distribution of predicted hazard and observed water quality for all parameters concerned. However, the fact that a *potential* hazard was not fully realised during the sampling programme does not make the predictions necessarily wrong. It is the physical characteristics of the catchment area and the activities taking place within it that represent the actual hazard to water quality. As with any spot sampling programme there was the potential for general trends and events to be missed by the sampling programme.

The ability to predict absolute values from the identified potential hazard has proved limited for several water quality parameters. However, as was outlined in the original aims of the thesis, it is not within the scope of a generic risk assessment methodology to accurately predict absolute water quality values. The hazard identification stage is designed to identify all areas of catchment that have the *potential* to affect water quality at the intake site.

Chapter 9

Estimating hazard probability and evaluating risk consequence

9.1 Introduction

In establishing a catchment risk assessment methodology, the majority of this thesis has been concerned with the establishment of a philosophy for generic risk assessments and the development of novel methods for determining the location and geographical extent of pollution hazards in a catchment area. As a result, discussions in the previous two chapters have purposely related to hazard as opposed to risk. In order to extend beyond the stage of hazard identification, some consideration of hazard frequency and consequence i.e. hazard estimation and risk evaluation, must be considered in order to complete the assessment of risk. Some of the potential consequences of pollution hazards being realised have been touched upon in Chapter 6, highlighting the need to distinguish consequence when assessing risk.

The first section of this chapter describes some examples of how historical data, results of the sampling programme and generic statistics are applied to the Upper Wharfe catchment to estimate hazard frequency. The second half of the chapter then determines different levels of risk consequence and their resultant effect on drinking water quality. The concepts of consequence trees, introduced in Chapter 5, are developed and a risk consequence index to determine potential effects of a “risk event” proposed.

9.2 Hazard estimation

Numerous methods were proposed in Chapter 5 for determining estimates of hazard probability. Examples of these as applied to the Upper Wharfe catchment are given below and comments about their suitability for practical applications made. Particular importance is paid to retaining the generic principles identified in earlier chapters.

9.2.1 Spatial analysis of historical data in GIS

The analysis of historical data sources using GIS has been investigated in Chapter 6. However, here we are concerned with the frequency of occurrence. With the historical data describing pollution incidents we can prepare an estimate of annual frequency. Data describing the location of pollution incidents are only currently available for the period 1994 to 1997 for the Upper Wharfe area. From this information the following frequencies of pollution incidents have been determined.

Again this was carried out automatically in MapInfo, where historical incidents were interrogated on a sub-catchment scale. The predicted number of pollution incidents was calculated as the average number of incidents in each sub-catchment over the period 1994-1997. These are shown in Table 9.1.

Table 9.1 Pollution incident frequency estimates – Upper Wharfe by sub-catchment

Sub-catchment	Frequency (average occurrences per year)	Return period (days)
Barden	0.667	547
Grimwith	0.333	1096
Halton	3.000	122
Howgill	0	-
Kex Beck	0	-
Langstrothdale	2.667	136
Littondale	0.667	547
Main River 1	13.000	28
Main River 2	0.667	547
Main River 3	1.667	219
Main River 4	0.333	1096
Whole River (Lobwood)	23	15

The data used above are freely available for any catchment in England and Wales from the Environment Agency. From this historical data it can be seen that the smallest return periods are experienced in the Main River 1 sub-catchment where a pollution incident can be expected every 28 days. This contrasts greatly with other sub-catchments where either no pollution incidents have occurred, none have been recorded, or the predicted return period is up to three years (1096 days). The overall predicted return period for a pollution incident the Upper Wharfe catchment is 15 days. For the catchment as a whole, data are available for several years previous to 1994. During the 8 years for which pollution incident information is currently available in the Upper Wharfe there have been 481 incidents, which indicates a probable return frequency of one incident every 6 days.

These predictions are restricted by the limited amount of data available, especially geo-referenced information for the Wharfe that would allow the assignment of return periods to individual sub-catchments. However, as these incidents are now collated on a central database and in common format the amount of available information will increase with time. Hence the potential of this approach for generic risk assessment will grow.

9.2.2 Raw water sampling – comparison to legislative standards

Where sampling programmes have been established for the purposes of risk assessment, such as that outlined in Chapter 8, data can be used to identify hazard probability and return frequencies for individual sub-catchment areas by comparison to legislative standards.

Only five of the monitored parameters are of relevance to the 1975 Surface Waters (Classification) Regulations. Of these only the limit for colour was exceeded at any point in the catchment. This was exceeded 12 times at Grimwith and once at each of Howgill and Kex Beck. No values above the regulatory standards were seen at the intake site itself. The only information that can be gleaned from this is predicted return periods of 25, 304, and 304 days respectively for colour incidents in the Grimwith, Kex Beck and Howgill sub-catchments.

With the drinking water regulations there are many more parameters stipulated and hence more data to consider. As discussed earlier, this also incorporates a considerable "safety factor" in the estimate of risk. Breaches of the PCV standards for drinking water in the Upper Wharfe sub-catchments were calculated from the sampling programme results for all sites, and most importantly for the intake site at Lobwood. Frequencies of between 0 and 318 days per year were calculated for various parameters at the intake, as shown in Table 9.2 below.

Table 9.2. PCV failure frequencies in raw water at the Lobwood intake.

Parameter	Predicted PCV failure rates from sample results (days per year above PCV)
Colour	318
Turbidity	56
Total phenols	9
Nitrate	0
Bacteria (all)	365
Aluminium	65
Iron	112
Manganese	9
Cryptosporidium	0

However, this approach relies on very catchment specific data for a particular intake sites and would therefore not be generically applicable where a catchment is not routinely monitored.

As with all of the applications of sampling data discussed in the research, only more information would be able to define whether extreme events are predicted correctly, and continuous sample collection and/or monitoring would be necessary for this purpose. However, the nature of such intensive sampling is again inconsistent with the aim of producing a generic methodology. Therefore although this approach is suggested in Chapter 5 as one potential use, it would not be generally applicable to other catchments due to the lack of continuous monitoring. Such an approach would be ideal where continuous automatic monitoring takes place at an intake site and can be applied in this catchment due to the large amount of sampling information present.

9.2.3 Use of generic failure data / macro-scale statistics

This represents a further method of determining risk frequency where no other data are available. Due to the limited number of positive oil and greases sample results, the example of spills from road traffic accidents has been selected as an example here.

Road traffic accidents may have a major impact on a water supply intake. The main hazards that exist are from the bulk transport of liquid substances in large tankers. Information about the road network can be combined with accident and spill statistics to give a probabilistic assessment of a spill occurring in the catchment. Equation 9.1 (adapted from Cole and Lacey, 1995) was used to calculate the total road spill risk in a catchment area.

$$\text{Total_Road_Spill_Risk} = \sum_{i>0}^{i=n} [L \times F(0.1) \times A \times P_i] \quad (\text{Equation 9.1})$$

Where: L = total length of road of a particular class in the catchment,

F = average flow of Heavy Goods Vehicles (HGVs) per year,

0.1 = proportion of HGVs that are bulk tankers,

A = accident involvement rate per million vehicle kilometres travelled,

P_i = probability of a spill of size i occurring as a result of an accident.

This could be carried out in either GIS software package. In MapInfo, a MapBasic program was written to extract the relevant data from the attribute tables and calculate the equation. An information box was then displayed on-screen to show the result. Such attribute analysis can also be done easily in WINGS by creating a DUMP macro to extract the relevant information from the selected data layers. Expected probabilities were calculated for two classes of road, Primary routes and Minor routes and are shown in Table 9.3.

Table 9.3 Probability (per year) of a tanker spill occurring in the Wharfe Catchment

Spill size (kg)	Primary Routes	Minor Routes	Total
Less than 150	0.0360	0.0048	0.0408
150 – 1500	0.0090	0.0010	0.0100
1500 +	0.0200	0.0030	0.0230
Total	0.0650	0.0088	0.0738

Two primary routes represent a major potential hazard in the Wharfe catchment due to their extended proximity to the watercourse. Table 9.3 shows that a spillage from such a route is predicted approximately once every 15½ years of operation ($p=0.0650$), compared to once every 188 years ($p=0.0088$) for minor roads. The potential exists for this approach to be enhanced by using link-specific traffic flow data and accident rates, and determining the extent of highway drainage.

Probabilities calculated in this manner can be assigned to individual links in the road network data to provide estimates of the spatial distribution accident hazard. An example of this was seen in the Oil and greases hazard map in Figure 7.8.

9.2.4 Coupling GIS analysis with water quality models: water discoloration and trace metal mobilisation

Past research (e.g. Mitchell and McDonald 1992 & 1995) has yielded a number of predictive models describing the relationship between catchment characteristics and stream water quality. Here the ability of the GIS to analyse several large files of spatially referenced data is used to quantify water discoloration and aluminium concentrations at a sub-catchment outlet using such models. The equations, based on step-wise multiple regression, are as follows:

$$\log_{10} \text{Colour} = 0.00512 (\%TCLA_5^0) - 0.609 (\text{MSS}) + 0.00368 (\%1011b) + 0.21435 \quad (\text{Equation 9.2})$$

$$\log_{10} \text{Al} = 0.034 (\%TCLA_5^0) - 10.0019 (\text{RR}) - 0.653 \quad (\text{Equation 9.3})$$

Where: $\%TCLA_5^0$ = percentage of total channel length in areas of less than or equal to 5° slope,
 MSS = main stream slope (slope between 10 and 85 percentiles of main stream),
 %1011b = percentage of catchment area of soil type 1011b (Winter Hill Peat),
 RR = Relief ratio (Basin relief / basin length)

These models, developed by Mitchell & McDonald (1992), have been found to explain 82% and 68% of variations in colour and aluminium respectively in upland catchments similar to the one being studied here. Considering a small sub-catchment as an example, Table 9.4 shows predictions of colour and how these compare to values obtained by on-site sampling. In general the mean values were over predicted for this sub-catchment, with the predictions for colour actually being closer to the maximum values obtained from the sampling. Predicted values can potentially be compared to the water quality regulations to determine frequency estimates.

Table 9.4 Predicted and actual values of Colour and Aluminium in Littondale

	Colour (Hazen)	Aluminium (mg ^l)
Predicted value (mean)	46.54	8.02
Maximum (from sampling)	45.70	0.24
Mean (from sampling)	19.16	0.06
Minimum (from sampling)	0.01	0.01

The variable results seen here illustrate the hazard of transferring predictive models created for other catchment areas. However, it was seen that model input parameters can be easily determined using a GIS. New predictive models, specific to the study catchment and based on GIS determined variables such as the examples given in the previous chapter may predict values more successfully. The above examples are used to show the potential application of generic relationships identified from other catchment areas.

9.2.5 Logic tree analysis for frequency estimation

This method lends itself best to the consequence tree approach as the cumulative effect of frequency statistics can be accounted for in this way. It involves the mathematical combination of probabilities on the arms of the Consequence Trees described in the next section. However, unless generic statistics are available for plant failures and process systems, they will again rely heavily on historical data. Such data is becoming increasingly available as a result of Reliability Centred Maintenance (RCM) programmes throughout the water industry, but at the present time insufficient data exist for generic, quantitative predictions to be made with confidence. It is suggested therefore that subjective labelling of consequence trees can be used to facilitate this if and when consequence trees are used for the risk consequence analysis.

9.2.6 Subjective assessments

Where absolute values are not widely available to enable generic risk assessments then estimates of hazard frequency can be determined subjectively. A qualitative ranking of, *never, seldom, frequent, more frequent, continuous*, is a valid estimate of hazard probability. Although such qualitative approaches are less common in engineering and industrial risk assessments, they are a suitable approach for environmental processes that are often less well understood. These can be determined from a general feel for the water quality or activities in a catchment area, although the extrapolation of these from limited historical data can also be a useful approach. In order to show an example of subjective frequency assessment, the parameters considered above for the Upper Wharfe catchment are categorised using such a scale in Table 9.5 below. These are subjective estimates based on a combination of all available information sources referred to in the research. Five categories are again presented in the classification, following the protocol of the hazard identification stage.

Table 9.5 Subjective classification of hazard frequency in the Upper Wharfe

Frequency class	Water quality hazards
Never	N/A
Seldom	Nutrients, pesticides, phenolics
Frequent	Cryptosporidium, oils & greases
More frequent	Aluminium, iron, manganese
Continuous	Colour, bacteria

Where a truly generic methodology is to be employed the use of such subjective classification can greatly assist in the preparation of frequency estimates as can be based on very little input data. However, this approach also has the greatest potential to mislead, should the classifications be wrongly interpreted or not applied consistently.

9.3 Risk evaluation

Evaluating risks to water supplies entails consideration of the magnitude of the impact and its potential “ripple effects” and “signal strength” alluded to in earlier chapters. That is, what does the realisation of a risk actually mean in terms of both quality of the drinking water, the impact on customers and the potential negative effect of adverse publicity for a water supply company with insecure or polluted resources. A number of the approaches suggested in Chapter 5 are again investigated below.

9.3.1 Comparison with DWQ regulations

This approach was again recommended as a potentially generic method for conducting a stage of the RASCAL process. As with previous comparative measures, it was found to be very data intensive, relying heavily on the use of regular and complete sampling data. The approach can be combined with the similar approach to frequency estimates described above, but essentially water either passes or fails the drinking water quality regulations. It is the individual (or collective) effect of the substances concerned that influences public health, i.e. a PCV failure by $100 \mu\text{g l}^{-1}$ is no worse than one by $1 \mu\text{g l}^{-1}$, if public health remains unaffected.

As with the frequency estimate approach described above where sample results are compared to the values stipulated by the drinking water regulations, the potential for generic application of this approach is limited to those sites where continuous monitoring is available. However, if such information were available then the analysis of results using the a revised version of the PARI index method proposed by Lamb & Keller (1992). A ratio of the observed values to the regulatory standards would enable a measure of the consequence to be achieved. Where values greater than unity (1) were identified, a significant risk would be present. However, only the consequence of regulatory failure can be assessed in this manner. Additional impacts in such cases are therefore the financial and perceptual costs to the supply company are omitted.

9.3.2 Loss of yield estimates

For the Lobwood intake, loss of yield estimates due to intake shut down should be calculated at a rate of 91 Mld (megalitres per day), the maximum daily abstraction at the site. From such estimates, the potential exists for water supply companies to determine the associated impact on operating costs for the treatment and distribution system affected. Thus a cost-benefit analysis of proposed catchment management activities can be prepared. However, such an approach may also fail to consider the potential impacts on public health and the indirect costs associated with a prosecution, or poor public image of a supply company.

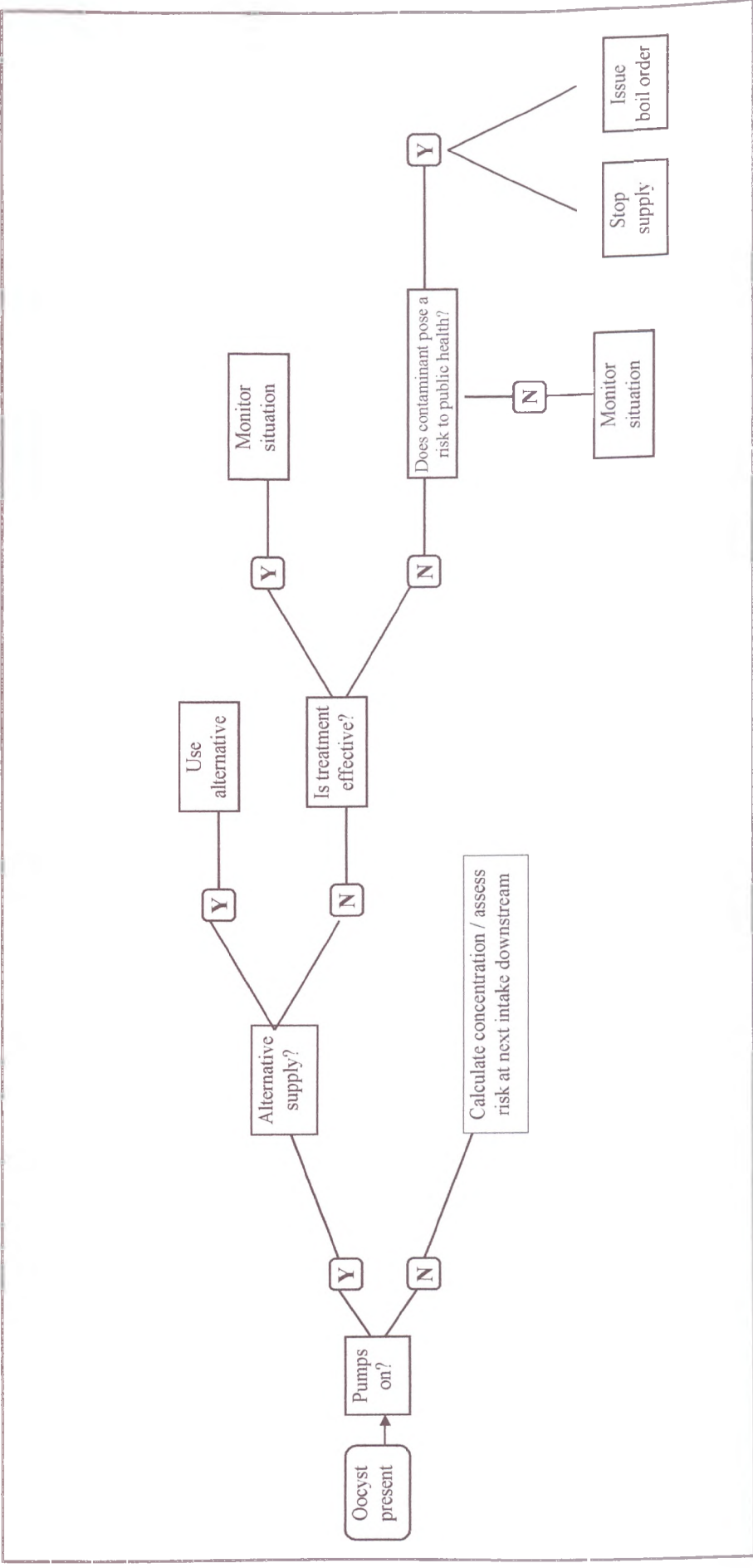
9.3.3 Consequence Trees

The consequence trees suggested in the initial framework were created for several of the water quality parameters under consideration. An example of one for cryptosporidium can be seen in Figure 9.1 overleaf. Once these are created they can be applied to various catchment areas, with minor variations to account for changes in the intake or treatment processes in place. Such trees also facilitate the calculation of frequency statistics where generic or site specific failure data are available.

However, for many pollution incidents multiple contaminants may be present. Their combined effect may be additional, subtractive, or multiplicative depending on the nature of the pollutant. Such scenarios of multiple pollutants are extremely difficult to model using the consequence tree approach as trees must either be cross-referenced to each other, or complex, interconnected trees developed. Thus the need to provide clear, generically available information is lost.

The principle of consequence trees can be effective and may be used when simple pollution events are present, or the interaction of various contaminants well understood. However, in order to be fully generic, a more subjective approach to risk evaluation is required.

Figure 9.1 Cryptosporidium consequence tree



9.3.4 The consequence index approach

The above methods of assessing risk consequence evaluation are inherently quantitative in approach and may require considerable amounts of input data, making them unsuitable for generic application to all catchments, especially those where monitoring information is sparse. However, the generic principles incorporated in these can be extracted to develop a subjective index of risk consequence. Risk consequences can be described in terms of source security and treatment plant efficiency, human toxicity / public health, and regulatory failure

Source security and treatment plant efficiency

Both the security of a source and the treatment processes in place will influence the significance of a pollution hazard. This requires an understanding of the distribution networks in order to determine whether the source under consideration is the sole, primary or partial resource bank for a certain supply area. The ability to divert resources or obtain water from alternative areas will greatly increase the security of a water distribution network. Such approaches have been widely used in the management of upland catchments for the reduction of discoloration (McDonald *et al*, 1991).

The efficiency of the treatment plant in place will also greatly influence the impact of a pollution event on the quality of the final drinking water. For example if certain problematic chemicals can be effectively treated by the plant in place then the resultant consequences will be less significant, and the consequence classification reduced.

McDonald (1995) recommends the use of catchment profiling in which *green*, *blue*, *yellow*, and *red* catchment labels are used to indicate the security of a particular source. These are based on variables describing service fragility (i.e. alternative sources of supply), treatment capacity, risk reduction capacity and risk potential. This approach requires careful consideration of both the supply network and treatment processes involved.

Human toxicity / public health

The primary consideration in determining the consequence of the pollution of drinking water is the health of consumers. Consideration of published levels of human toxicity allows a potential pollutant or its derivatives to be assessed in terms of its effect on public health, should it contaminate drinking water supplies. Toxicity levels for drinking water are incorporated in the drinking water regulations through the recommendations of the World Health Organisation (WHO). Little is known however, about the long term, carcinogenic effects of low levels of certain chemicals. It is therefore extremely difficult to include these in regulatory levels. The US Environmental Protection Agency (EPA) has developed Risk-Based Concentrations, taking into consideration both carcinogenic and non-carcinogenic effects. A subjective of the potential impact can therefore be established for a number of compounds from consideration of the types of toxic effects seen for common pollutants.

Regulatory failure

As discussed in earlier sections, water supply companies in England and Wales have a statutory requirement to ensure drinking water is wholesome at the point of supply. Failure to meet these requirements can lead to legal action and financial penalties. Costs resulting from such failures can also be realised in terms of public perception and image, with regular or high-profile failures resulting in a loss of consumer confidence and can therefore be difficult to quantify accurately. In such a case, a qualitative statement can be made about the consequence. e.g. “consequence A is likely to have an effect on costs” - rather than precisely defining the actual costs to the supply company.

The four concepts of risk estimation outlined above have been incorporated into the consequence index set out below. This allows all hazards to be categorised by an index that indicates the potential consequences in terms of source security / loss of supply, potential impacts on public health, and the costs to the supply company associated with supply losses and / or failure of regulatory standards.

The idea of consequence indexes stems from the need to communicate the vast number of possible outcomes of an individual event in a simple, clear manner. The index combines the concepts of health effects and regulatory / financial penalties discussed above, as well as regulatory failures statistics evident in quantitative assessments. There are five levels to the index as set out in the table below. Again these classes are subjective, their boundaries can be delimited by either absolute values (i.e. quantitatively), by some more qualitative measure such as those shown in the table itself.

Table 9.6 Consequence Index definitions

CONSEQUENCE CLASS	TYPICAL CONSEQUENCES / INCIDENT CHARACTERISTICS
ZERO	<ul style="list-style-type: none"> • No pollution evident at intake site. • Water quality within variations expected during uncontaminated periods. • Intake operation dependant on demand and resource availability.
NEGLIGIBLE	<ul style="list-style-type: none"> • Negligible pollution, any contamination removed by treatment. • Intake operation not affected. • Distribution activities & quality unaffected. • Situation requires monitoring
MINOR	<ul style="list-style-type: none"> • Minor pollution incident. • Possible temporary shut down of the intake / further storage of abstracted water. • Abstraction quality regulations may be breached, more intensive treatment may be necessary. • Possibly some discoloration or taste / odour present in finished waters, possibly minor infections.
SIGNIFICANT	<ul style="list-style-type: none"> • Significant pollution incident necessitating intake closure • Some treatment plants may not be able to remove contamination • Limited supply alternatives. • Water Quality Regulations may be breached (both at the point of abstraction & supply). • Possible health impacts: serious gastrointestinal infections, potential hospitalisation of consumers.
MAJOR	<ul style="list-style-type: none"> • Major pollution incident necessitating closure of the intake • Refurbishment of plant & machinery. • Little or no alternative supply available. • Treatment works unable to remove contamination, • Failure of Water Quality Regulations at both the point of abstraction and point of supply. • Serious risk to public health if water is ingested: possibility of death / serious illness, hospital treatment required.

9.4 Conclusions – methods for assessing the probability of occurrence and consequences of pollution risks in supply catchments

Estimating the probability of a particular hazard occurring has been attempted in a number of ways. The method most suitable for a particular area depends on the information and resources available. Three methods are proposed, the analysis of historical data, the application of local and national statistics, and GIS-based modelling of known relationships between catchment characteristics and water quality. The availability of water quality data was identified as a fundamental barrier to the successful preparation of quantitative frequency estimates. It was concluded however that a quantitative estimate of probability is not always required and a more qualitative ranking of, for example, *never, seldom, frequent, more frequent, continuous*, is also a valid estimate of hazard probability. Although such qualitative approaches have been neglected in engineering and industrial risk assessments, they are considered a suitable approach here.

The most important finding of this chapter is that for several of the frequency estimation and hazard consequence methods proposed, large amounts of catchment-specific data are needed for accurate sub-catchment based estimates of hazard frequency. Therefore, in the more generic type methodology proposed here the use of generic failure rates, macro-scale statistics and simple modelling can provide the risk assessor with some indication of probable frequencies. For estimates of both hazard frequency and risk consequence, it is subjective approaches that proved among the most suitable for the study catchment.

For a risk assessment to be truly generic it must therefore embrace quantitative, semi-quantitative and qualitative approaches to assessing risk.

All comparison to regulatory standards requires a considerable amount of catchment specific data, but a potential methodology for assessing consequence, a refined version of the PARI index (Lamb & Keller, 1987) has been proposed. In addition the use of consequence trees to model potential risk impacts has been tested and appears successful. Probabilistic and subjective weightings assigned to these tree 'branches' can also be used to estimate frequencies and return periods.

A consequence index has been developed to simplify the assessment of risk consequence. Risks events are described in terms of their potential impact on the operation of the intake, treatment and distribution processes, the potential for alternative supplies, potential effects on public health, and the costs to the supply company resulting from failure of regulatory standards. The main benefit of such an approach is in the improved communication of risk assessment findings. The consequence index developed above represents a truly generic approach to determining risk consequence and is therefore ideal for incorporation in generic approach such as that being sought here. A number of such indexes can potentially be created depending on the abilities of the assessors and the audience of the risk assessment.

Chapter 10

Conclusions, summary of findings and future directions

10.1 Conclusions and summary of research findings

The aims and scope of the research were presented in Chapter 1 and the subsequent chapters have achieved these aims. The primary aim of the research was to develop a methodology using GIS technology to assess pollution risks to potable water supply intakes such as those in the Yorkshire region. This has been achieved through the development of the Risk Assessment of Supply Catchments And Land (RASCAL) methodology.

The context of the research was established through a detailed review of the three disciplines encompassed by this research: drinking water quality, geographical information systems and risk assessment. The conceptual framework of the methodology was then developed in Chapter 5. Following this, specific techniques and approaches were developed and refined further by example application to the Upper Wharfe catchment in Yorkshire. Particular attention was paid to the development of novel methods of identifying hazards to water quality through the exploitation of GIS-based technology and the creation of catchment hazard maps. Further discussions also lead to the development of generic approaches for the estimation of hazard frequency, and assessing and communicating the consequences of a risk event.

The following discussion summarises the conclusions of the development stages of the methodology and then outlines the methodology itself. The thesis is then concluded with some suggestions for future research directions building upon the findings presented here.

Chapter 2 established the context of the research by discussing the current and historical characteristics of drinking water legislation and identified water quality issues of national and regional significance. In general, the compliance of drinking water supplied by the 10 major water service companies was found to be improving, but the pollution of raw water sources was identified as a major potential source of non-compliance. Catchment management was identified as having significant potential for the control of raw water quality and the importance of identifying causal activities in catchment areas highlighted. The need for a coherent risk assessment methodology for intake catchments was therefore established from the perspective of safeguarding public health, increasing regulatory compliance and reducing the cost of treating raw waters

Discussions in Chapter 3 regarding the use of GIS in the UK water industry illustrated the increasing use of GIS and digital mapping activities for the strategic planning of operational activities. Past uses of GIS technologies were found to be limited to digital mapping activities, but as a greater understanding of the potential applications and ability of GIS has developed in the industry, so their use has expanded.

Despite applications to other environmental risk assessments, the potential for using GIS in the assessment of pollution risks to a surface water intake has remained largely unexplored. The ability of GIS to store, analyse and display spatially referenced data makes such systems ideal for use in risk assessments at the catchment scale. The formulation of a methodology to assess pollution risks in a water supply catchment which utilises the power of GIS to handle large volumes of spatially referenced data was therefore considered particularly timely.

Turning to the context of risk and risk assessments, the fundamental concepts of hazard and risk have been defined in direct relevance to the assessment of drinking water pollution risks. Such risks were identified as societal and involuntary in nature due to their potential to impact on large numbers of unaware receptors. The concepts of dread factors and signal potential were discussed and the position of drinking water source pollution in conceptual “factor space” hypothesised. It is hoped that the consideration of drinking water quality risks in these terms will encourage those involved in conducting assessments such as that described here to think of risk in the wider context of societal and social impacts.

The basic stages of an environmental risk assessment process were identified as hazard identification, hazard estimation, risk evaluation and risk management. Several approaches for each of these four stages was discussed and those suitable for incorporation in the methodology being developed transferred to Chapter 5. In Chapter 5, six previous examples of pollution risk assessments were appraised and their relative merits discussed. Those concepts that could be utilised in generic approaches were identified and problems in the previous application of similar methodologies highlighted. Such problems, essentially encompassed a desire by previous authors to consider only one type of risk assessment, usually a quantitative approach, which resulted in a considerable lack of flexibility in the methods employed. In addition, these previous approaches were seen to be based on the acquisition of large amounts of historical or background data. Such approaches are inherently inappropriate for a generic methodology.

From the background summarised above, the Risk Assessment of Supply Catchments And Land (RASCAL) methodology was conceived carried out on the Upper Wharfe catchment. The RASCAL process was partitioned into the four stages of environmental risk assessment identified earlier and then specific recommendations of the literature survey and conceptual development tested by example application to the Upper Wharfe. The development of the four stages is summarised below.

10.2 Risk Assessment of Supply Catchments And Land (RASCAL) - a generic methodology for catchment risk assessment

10.2.1 Hazard identification

In order to be truly generic, the methodology was based on the use of commercially accessible GIS software and data, secondary data archives (such as national statistical records) and field studies. This will allow the methodology to be applied on other catchment areas in the future and result in a generic, consistent approach to assessing pollution risks.

It was recommended in Chapter 5 that initial indications of potential hazards were identified from historical data describing river water quality and pollution incidents. However, even for a relatively well studied river such as the River Wharfe, insufficient water quality data could be obtained to give anything more than general indications of potential hazards. This failing was common to previous studies, and the second stage of the hazard identification process was therefore utilised to the greatest extent in the study of the Upper Wharfe.

Generically available digital data were identified for the Upper Wharfe (from Yorkshire Water's GISLAB initiative) and hazard maps produced for ten water quality issues. Existing knowledge of potential source areas and mobilisation conditions were combined in Source Trees. These were then used as the basis for the GIS data models from which the hazard maps were built in MapInfo. Using this approach the probable extent of point and diffuse sources of pollutants were identified for the entire catchment of the Lobwood surface water intake. This mapping represents a significant improvement in the way that potential hazards can be identified. Not only is the process automated, but the production of maps that can be interrogated on any scale allows significantly better communication of the outcomes of a risk assessment.

GIS-based mapping techniques were also used to develop a raw water sampling programme to investigate the spatial distribution of water quality in the catchment. The main catchment area was sub-divided into 12 sub-catchments and water quality samples collected weekly for a 10 month period. The results of this sampling showed distributions in water quality similar to those suggested by the hazard mapping exercises, although the limited data resulted in few statistically significant correlation coefficients between the hazard maps and observed values.

The scope for using GIS for visual representations of hazard has been identified and proven by the creation of hazard maps from which individual hazard sources can be identified down to the field scale.

10.2.2 Hazard estimation

Hazard frequency was estimated in a number of ways for the parameters under consideration in the Upper Wharfe catchment. Of the approaches suggested in Chapter 5, it was the use of generic statistics and subjective approaches that proved the most suitable for application to the study area.

Initial predictions were obtained from the spatial analysis of pollution incident data using MapInfo, however the limited availability of suitable data meant that these predictions were based on just three years information. The second approach was to compare the values to the drinking water regulations relating to both surface water and treated water quality standards. However, this approach again suffered from a lack of suitable information and continuous data for the intake site and sub-catchment outlets.

The availability of water quality data was identified as a fundamental barrier to the successful preparation of quantitative frequency estimates. It was concluded however that a quantitative estimate of probability is not always required and a more qualitative ranking of, for example, *never, seldom, frequent, more frequent, continuous*, is also a valid estimate of hazard probability.

The most successful approaches to estimating hazard frequency for a generic approach involve the use of macro-scale statistics, such as national or regional accident statistics, and simple water quality models describing the relationship between water quality and catchment characteristics. Although such models require large amounts of information about individual catchments, it has been shown in this work that appropriate variables can be readily determined by the analysis of commercially available digital data on a desktop PC using the MapInfo GIS software package.

These models have significant potential to assist in risk assessments in supply catchments, especially in prediction hazard frequency values. However, they are still in relatively early stages of development and more empirical research into models applicable to a wide range of catchment areas is required.

10.2.3 Risk evaluation

Numerous methods of predicting and describing hazard consequence were also tried on the Upper Wharfe study catchment. Again however, it was the subjective approaches that proved most suitable for this catchment and a generically-based approach as a whole.

Comparative analysis of sampling observations and water quality regulations was again suggested, but relied on sporadic, spot sampling data and resulted in the need for a considerable amount of site specific information. Again, such an approach would be well suited where continuous on-line monitoring for numerous parameters is carried out at the intake site, but is not suitable for generic application to non-instrumented sites.

Loss of yield estimates could potentially be calculated for the intake, as with the comparisons to regulatory standards, these take little account of the wider impacts of public health and indirect costs to the supply companies.

Consequence trees were identified for several parameters. These were seen to be successful for describing simple pollution events and have significant potential for determining risk frequency when combined with suitable data. However, the flexibility of this approach was found to be limited where multiple pollutants may be present, especially if their combined effects are poorly understood

The method of evaluating risks recommended for generic applications is therefore the use of a consequence index. Such an index can be described in terms of source security and treatment plant efficiency, human toxicity / public health, and regulatory failure. A recommended format of this index is give in Table 9.6 in the previous chapter. Most importantly, consequence indices such as that outlined in this research can be based on either quantitative or qualitative approaches, or indeed a combination of the two.

10.2.4 Risk management

When considering a generic methodology the concept of preparing recommendations for risk management may seem somewhat inappropriate. However, as illustrated by Figure 5.1, this fundamentally important stage allows the feedback of information to future iterations of a risk assessment process.

Risk management involves identifying actions that may be used to reduce risks to the supply intake, and formulating plans for the implementation and monitoring of these actions. This will be influenced by the amount of control the supply company has over the catchment area. Actions taken will also be subject to land ownership, tenancy agreements and planning constraints and will require close co-ordination with organisations such as the Environment Agency and local Councils and the landowners and tenants of an area. All management actions should be monitored as to their effect on catchment risk by regular re-assessment exercises carried out at intervals applicable to the work undertaken.

Possible management options may include:

- amendments to tenancy agreements
- changes to recommended / encouraged land practices
- changes to the intake operating strategy
- up-grading of treatment works and processes
- re-design of distribution networks / alternative supplies

Management recommendations put forward as the result of a risk assessment will need to be tailored to a particular catchment area depending upon the hazard present, and overall assessment of risk. However, these management practises should encompass the key themes above that form part of the generic methodology.

10.3 Future research recommendations

Whilst the main research aim of developing a generic methodology has been achieved and the potential of GIS-based risk assessment explored, there remains considerable scope for future research in this relatively unexplored subject area. Below is a list of some of those areas in which considerable potential for future research has been identified. Some of these represent areas where this initial development could either be improved upon or developed in the future as a direct result of findings presented here. In addition a number of potentially interesting areas have been identified during the development of the methodology, but further investigation was considered beyond the immediate scope of this research. These were observed throughout all stages of the work, from the original literature surveys to the definition of the methodology itself.

The sociological dimensions of risk and their impacts on risk assessment and perception has received little attention from the engineering and scientific community managing the water environment. The potential therefore exists for extensive further investigation into the sociological aspects of these risks to complement new methodologies such as that developed here.

The positioning of drinking water source pollution in “factor space” hypothesised in Chapter 4 will vary considerably depending on the perception and awareness of the scientists, water company employees and customers questioned. The location theorised in this work is therefore not intended to represent the ‘correct position’ but to present a starting point from which further research or discussion can progress.

This initial methodology was developed in a relatively simple, rural catchment. However, many potable supply intakes contain large urban areas and complex catchment characteristics. The potential exists to develop the approaches identified here to include larger urbanised areas with a subsequent increase in both point source hazards and diffuse contributions from urban drainage networks.

The identification of potential point sources could be further automated through the use of electronic databases such as the Electronic Yellow Pages or postcode address files which will identify categories of buildings. Such an approach would be ideal for the extension of the methodology to more urbanised catchments as discussed above.

Limited use of sample results could be made in the assessment of the hazard identification maps and estimating risk frequency due to the nature of the spot sample programme. Further sampling would therefore enable the use of this source of data for more in-depth analysis of hazard location and

frequencies. This would move away from a generic method of assessment to a more catchment-specific one. Such an approach would be ideal for further iterations of the risk assessment process, following a generic assessment such as that developed here.

One approach to identifying the initial scope of hazard identification was found to be the comparison of historical quality records with standards set in the various water quality regulations introduced in previous chapters. However, this is constrained by the limited number of parameters that are routinely monitored at intake sites. More intensive monitoring of known risk parameters following a successful initial risk assessment could help reduce this problem for future iterations of a risk assessment.

There also remains scope to use GIS analysis to relate historical pollution incidents to catchment characteristics once the database of geo-referenced pollution incident data grows with time. Such relationships could then be used to predict more accurately the location and extent of future pollution events.

A large amount of water quality information was collected as part of this study. It is therefore intended that further research will be conducted into the relationship of these variables with catchment characteristics in the Upper Wharfe. The potential also exists to investigate the hazard mapping variables using discriminant analysis.

There is also potential for numerous investigations to be carried out into the estimation of hazard frequency. Some initial estimation methods that suitable for generic applications have been identified here, but there is scope for future development as subjective methodologies become more widely accepted by the scientific and engineering communities that often represent the decision makers in the UK water industry.

Where site specific risk management scenarios are identified, the use of automated risk assessment techniques such as the GIS methods developed here could be used to facilitate a cost benefit analysis of the options to determine either the financial or environmental implications of a management proposal.

Many of the areas identified above represent deeper investigations into quantitative predictors for site specific risk assessments. However, the fundamental concept illustrated in this research is that these can be used in conjunction with more subjective estimates of risk. Further investigations should therefore take place to enhance existing risk assessment methodologies, such as those discussed in Chapter 5, using a more subjective approach.

10.4 Summing up the RASCAL approach

A fundamentally important characteristic of the RASCAL methodology, that makes it truly generic, is the mixture of quantitative, semi-quantitative and qualitative techniques that are encompassed within it. Not only are complex geographical modelling techniques used to identify potential source areas, but the potential of subjective indices to describe frequency and consequence is identified. For estimates of both hazard frequency and risk consequence, it was these subjective approaches that proved most suitable for the study catchment. This therefore represents a significant contrast to the traditional hard-engineering approaches to risk assessment applied in past studies where the emphasis has been on the quantitative calculations of absolute values and frequency measurements.

The potential application of GIS techniques in risk assessments has been identified and its success illustrated. The storage and analysis of digital spatial data in a GIS has formed the basis of the RASCAL methodology, and was especially successful in facilitating hazard identification in the catchment. The mapping of hazards is of considerable importance for the successful communication of the risk assessment process. Although GIS were used in several of stages of the risk assessment process described here, the potential for further use will increase as their flexibility and analytical capabilities increase.

The generic methodology developed here has a number of potential benefits for all stakeholders in the water industry and beyond. By using a generic approach such as this water supply companies can ensure a consistent assessment of water quality risk. This will allow the optimisation of their resource use across the whole of their operating area. It also provides a potential area of expertise in which to grow the businesses outside of the regulated industry. Regulators can benefit from such an approach as they can clearly see how risks are assessed and therefore consider whether these risks have been successfully managed. The GIS based approach described in this work is also particularly suitable for communicating risk assessments to customers and outside bodies. The production of mapped images on a variety of scales can be used as a powerful way to describing the potential risks, highlighting concerns and predicting future catchment management scenarios.

Academically the thesis has combined three disciplines (water quality, GIS and risk assessment) with the common aim of producing a generic approach using the best available data. Such a transfer of ideas has not been successfully applied in this context previously and several suggestions have been put forward to show the potential of such approaches.

Above all else, it is hoped that this research into the development of a generic approach has illustrated the complex environmental and management systems that influence the quality of intake water, and will subsequently provide a vehicle for opening discussions on the application of new technologies, especially GIS to water quality risk assessments. It is also hoped that the approach of future assessors will evolve beyond strict applications of quantitative risk assessments towards more generically applicable and useable techniques, ideally utilising a mixture of quantitative and qualitative methods and harnessing the vast potential of digital spatial analysis to facilitate this. The importance of seeking stimulation from various disciplines, such as the social sciences and information technology, cannot be underestimated in the development of new methods of assessing risk to potable water supplies.

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Appendix A

Digital data summary

Appendix A – Digital data summary

Data	Attributes	Data Type	Coverage	Resolution / Scale	Source	Copyright / Licensing agreements
Abstraction licences	Licence no., status; source type, general use; aquifer name; licensed daily amount; licensed annual amount; licence holder's name & address	Point	YWS Region	N/A	Yorkshire Water / Y&H NRA.	Data supplied to YWS under licence from NRA. Use restricted to YWS projects.
Agricultural census data (1988 census)	Total farmed area; grassland; rough grazing; woodland; other land - e.g. Yards / recreational / buildings; total crops & bare fallow; total cattle & calves; total pigs; total fowls; total horticultural crops; total sheep	Polygon	Wharfedale	2km x 2km tiles	Edinburgh Data Library	Supplied free of charge for research purposes; must acknowledge the source (EDINA)
Basedata	Motorways (inc. Junctions & services); A Roads (single & double carriageway); Primary Routes (single & double carriageway); B Roads; Minor/Other Road; Toll; Railways; Coasts; Rivers; Canals; Lakes; Reservoirs; Urban Areas; Small Islands; Towns; Villages; Cartographic Names; (Settlements etc.); Gradient, 1 in 7 or Steeper; National Boundary; County Boundary; District Boundary; Tunnel; Airport; Ferries; Seaward Extension; Headland; Bridge	Point, Line & Polygon	Northern England	1:625,000	Yorkshire Water Services (from OS)	OS Copyright. Use restricted to YWS projects.
Boundary-Line data	District Ward; District Ward Seed Point; Electoral Division; Civil Parish/Community; District; County; Westminster Constituency; European Constituency; Non-Electoral Division; Non-Civil Parish	Polygon	Wharfedale	1:10,000	Yorkshire Water Services (from OS)	OS Copyright. Use restricted to YWS projects.
Consented discharges	Consent no.; consent conditions	Point	Wharfedale	N/A	Map layer created (by JF) from NRA / EA paper records	Public register data
Height data (Contours) - OS Land-Form Panorama	Height (above sea level) at 10m intervals; spot heights; lakes	Line	Wharfedale	1:50,000 (20km x 20km tiles)	Yorkshire Water Services (from OS)	OS Copyright. Use restricted to YWS projects.

Data	Attributes	Data Type	Coverage	Resolution / Scale	Source	Copyright / Licensing agreements
Height data (Slopes):- tins	Slope; aspect	Polygon	Wharfedale	TINS derived from 1:50,000 contours	Created in ARC/INFO in the School of Geography	OS Copyright
Holiday Accommodation (Caravan sites)	Name, number of pitches; postcode	Point	YWS Region	N/A	Created by Yorkshire Water Services	Use restricted to YWS projects.
Holiday accommodation (serviced accommodation)	Name, number of rooms; number of places; postcode	Point	YWS Region	N/A	Created by Yorkshire Water Services	Use restricted to YWS projects.
ITE Landcover data	25 classes: sea/estuary; inland water; beach and coastal bare; saltmarsh; grass heath; mown/grazed turf; meadow/verge/semi-natural; rough/marsh grass; moorland grass; open shrub moor; Dense shrub moor; bracken, dense shrub heath; scrub/orchard; deciduous woodland; coniferous woodland; upland bog; tilled land; ruderal weed; suburban/rural development; continuous urban; inland bare ground; felled forest; lowland bog; open Scrub heath; (plus unclassified)	Polygon	Wharfedale	25m x 25m grid	Institute of Terrestrial Ecology Land Cover Map of Great Britain	Licensed to YWS by ITE. Use restricted to YWS projects.
Precipitation data	Standard annual rainfall (long term average 1941-1970); potential evapotranspiration; effective annual rainfall; max 2hr rainfall; max 24hr rainfall; max. Snow depth; winter rainfall acceptance potential	Polygon	Wharfedale	1km x 1km grid	Institute of Hydrology?	Use restricted to YWS projects.
Reservoir catchments	Name of YWS reservoir.	Polygon	YWS Region	Digitised from 1:50,000 maps	Yorkshire Water Services	OS Copyright Use restricted to YWS projects

Data	Attributes	Data Type	Coverage	Resolution / Scale	Source	Copyright / Licensing agreements
River network	NRA reach code; 1990-1995 GQAs; 1985-1993 NWCs.	Line	River Wharfe	Digitised from 1:50,000 OS maps	Yorkshire Water Services (from National River Authority)	OS Copyright Use restricted to YWS projects
River catchments (to gauging stations)	River name; gauging station; hydrometric reference number.	Polygon	YWS Region	Digitised from 1:50,000 OS maps	Yorkshire Water Services (created by Institute of Hydrology)	Use restricted to YWS projects
Soil data	Soil class; soil type; host category	Polygon	Wharfedale	1km grid (HOST & soil) and 100m grid (soil only)	Soil Survey & Land Research Centre	Licensed to YWS. Use restricted to YWS projects
Sites of Special Scientific Interest (SSSIs)	SSSI name, area	Polygon	YWS Region		English Nature	Licensed to YWS. Use restricted to YWS projects
Strategic data	Road, rail, airports and ferries; water features, cities, towns and other settlements; administrative boundaries; woods and land use; positioned names	Points, lines & polygons	YWS Region	1:250,000	YWS (supplied by OS)	OS Copyright. Use restricted to YWS projects

Data	Attributes	Data Type	Coverage	Resolution / Scale	Source	Copyright / Licensing agreements
Yorkshire Water Services' surface assets	Audit; borehole; break pressure tank; building; critical supply reservoir; combined sewer overflow; critical tower; coastal water outfall; clean water tank; detention tank; estuarial discharge; emergency sewer overflow; en-route storage reservoir; estuarine water outfall; incineration facility; impounding reservoir; inverted syphon; inland water outfall; manhole; pumping station; river intake; raw water pumping station; raw water reservoir; sewage control structure; suction tank; sea outfall; spring; sewage pumping station; service reservoir; sludge treatment facility; stream intake; sewage treatment works; tank; well; water pumping station; water tower; water treatment facility	Point	YWS Region	N/A	YWS	Use restricted to YWS projects.
Ordnance Survey raster maps	Raster 'pictures'. Text on 1:50,000 is held in a searchable gazetteer	Raster Tiles	1:1,000,000 1:625,000 1:50,000 (1:10,000)		YWS (supplied by OS)	OS Copyright. Use restricted to YWS projects.
Ordnance Survey vector maps	Buildings (with selected building names and house numbers); roads (with names and/or department of transport numbers); rivers, streams, drains, ditches, canals, lakes, reservoirs and ponds; fences, walls, hedges and banks; high and low water marks; railways (standard and narrow gauge); place names and descriptive text; triangulation points, bench marks and other height information; tunnel alignments, pylons, overhead structures and cables; administrative and voting boundaries	Points, lines and polygons	1:2500 (rural) 1:1250 (urban)		YWS (supplied by OS)	OS Copyright. Use restricted to YWS projects.

Appendix B

Soil HOST Classes & RPI rank

Appendix B - Hydrology of Soil Type (HOST) classes & RPI rank

29 hydrological groupings are distinguished according to the Hydrology of Soil Types or 'HOST' system described by Boorman, Hollis & Lilley, (1991).

HOST Code	Description	Impermeability rank (for RPI)
1	Free draining permeable soils on chalk and chalky substrates with relatively high permeability and moderate storage capacity	1
2	Free draining permeable soils on 'brashy' or dolomitic limestone substrates with high permeability and moderate storage capacity	1
3	Free draining permeable soils on soft sandstone substrates with relatively high permeability and high storage capacity	1
4	Free draining permeable soils on hard but fissured rocks with high permeability but low to moderate storage capacity	2
5	Free draining permeable soils in unconsolidated sands or gravels with relatively high permeability and high storage capacity	1
6	Free draining permeable soils in unconsolidated loams or clays with low permeability and storage capacity	3
7	Free draining permeable soils in unconsolidated sands or gravels with groundwater at less than 2m from the surface	3
8	Free draining permeable soils in unconsolidated loams or clays with groundwater at less than 2m from the surface	3
9	Soils seasonally waterlogged by fluctuating groundwater and with relatively slow lateral saturated conductivity	5
10	Soils seasonally waterlogged by fluctuating groundwater and with relatively rapid lateral saturated conductivity	4
11	Drained lowland peaty soils with groundwater controlled by pumping	N/A
12	Undrained lowland peaty soils waterlogged by groundwater	5
13	Soils with slight seasonal waterlogging from transient perched water tables caused by slowly permeable subsoil or substrate layers	3
14	Soils seasonally waterlogged by perched water tables caused by impermeable subsoil or substrate layers	4
15	Permanently wet, peaty topped upland soils over relatively free draining permeable rocks	5
16	Relatively free draining soils with a moderate storage capacity over slowly permeable substrates with negligible storage capacity	2
17	Relatively free draining soils with a large storage capacity over hard impermeable rocks with no storage capacity	2
18	Slowly permeable soils with slight seasonal waterlogging and moderate storage capacity over slowly permeable substrates with negligible storage	4
19	Relatively free draining soils with a moderate storage capacity over hard impermeable rocks with no storage capacity	2
20	Slowly permeable soils with slight seasonal waterlogging and moderate storage capacity over impermeable clay substrates with no storage capacity	4
21	Slowly permeable soils with slight seasonal waterlogging and low storage capacity over slowly permeable substrates with negligible storage capacity	4
22	Relatively free draining soils with low storage capacity over hard impermeable rocks with no storage capacity	3
23	Slowly permeable soils with slight seasonal waterlogging and low storage capacity over impermeable clay substrates with no storage capacity	4
24	Slowly permeable, seasonally waterlogged soils over slowly permeable substrates with negligible storage capacity	4
25	Slowly permeable, seasonally waterlogged soils over impermeable clay substrates with no storage capacity	5
26	Permanently wet, peaty topped upland soils over slowly permeable substrates with negligible storage capacity	5
27	Permanently wet, peaty topped upland soils over hard impermeable rocks with no storage capacity	5
28	Eroded peat. (This soils type is not mapped separately in England and Wales)	N/A
29	Permanently wet upland blanket peat	5

Appendix C

Sampling programme results – water quality data

Sample site 1	Cowside Beck @ Arncliffe																		
Date	Aluminium	Clostridium Perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	Cryptosporidium	E. Coli	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	pH	Total Ammonia	Total Coliforms	Turbidity
23-Oct-96	0.035	10	190	28.1	258	0	0	90	90	10	0.058	0.002	0.95	0.003	0.95	8.5	0.03	190	0.67
30-Oct-96	0.03	140	309	39.9	261	0	0.2	50	50	50	0.072	0.002	0.96	0.003	0.96	8.4	0.03	140	0.9
06-Nov-96	0.265	30	650	39.9	213	0	0	530	530	50	0.222	0.011	0.72	0.004	0.72	8.1	0.03	650	3.8
13-Nov-96	0.041	20	210	20.4	241	0	0	80	80	80	0.053	0.002	0.84	0.003	0.85	8.5	0.03	210	0.8
20-Nov-96	0.034	30	60	15.3	447	0	0	60	60	60	0.061	0.002	0.84	0.003	0.84	8.4	0.03	60	1.15
27-Nov-96	0.041	10	130	17.6	246	0	0.2	30	30	100	0.049	0.002	1	0.003	1	8.5	0.03	130	0.72
04-Dec-96	0.058	10	370	15.7	234	0	0	40	40	110	0.052	0.003	0.82	0.003	0.82	8.2	0.03	370	1.27
11-Dec-96	0.024	10	170	15.3	252	0	0	80	80	10	0.028	0.002	1.3	0.008	1.3	8.3	0.03	170	0.76
18-Dec-96	0.058	30	60	28.4	198	0	0	40	40	30	0.108	0.002	0.96	0.003	0.97	8.2	0.03	60	1.87
03-Jan-97	0.01	0	30	5.6	260	0	0.2	10	10	10	0.01	0.002	1.05	0.003	1.05	8.3	0.03	30	1.22
08-Jan-97	0.01	0	370	7.9	275	0	0	10	10	10	0.01	0.002	1.02	0.003	1.02	8.4	0.03	370	0.18
15-Jan-97	0.031	1	490	14	208	0	0	10	10	10	0.042	0.002	1.03	0.003	1.03	8.2	0.03	490	0.73
22-Jan-97	0.01	1	240	11.6	242	0	0	10	10	10	0.023	0.003	1.11	0.003	1.11	8.3	0.03	240	0.65
29-Jan-97	0.011	0	90	17.7	220	0	0.2	0	0	0	0.027	0.002	1	0.003	1	8.3	0.03	0	0.83
06-Feb-97	0.048	10	300	44.2	177	0	0	230	230	20	0.052	0.002	1.11	0.003	1.11	8.3	0.03	90	1.47
12-Feb-97	0.235	20	300	44.2	175	0	0.2	5	5	5	0.106	0.007	0.58	0.003	0.58	7.9	0.03	300	10
26-Feb-97	0.098	30	14	28.4	242	0	0	10	10	10	0.049	0.002	0.89	0.003	0.89	8.2	0.03	14	2.49
05-Mar-97	0.032	0	80	8.9	251	0	0	10	10	10	0.015	0.002	0.79	0.003	0.79	8.6	0.03	80	0.53
12-Mar-97	0.014	20	160	2	655	0	0	40	40	40	0.131	0.003	3.84	0.003	3.85	8.7	0.03	160	0.15
19-Mar-97	0.116	40	720	31.9	225	0	0.2	30	30	30	0.157	0.008	0.51	0.003	0.51	8.2	0.03	720	3.2
26-Mar-97	0.069	150	400	11.3	257	0	0	50	50	50	0.02	0.002	0.69	0.003	0.69	8.7	0.03	400	0.61
02-Apr-97	0.014	20	330	10.6	255	0	0	200	200	130	0.025	0.002	0.82	0.003	0.82	8.3	0.03	330	0.47
16-Apr-97	0.01	10	3900	7.5	262	0	0	70	70	70	0.01	0.002	0.85	0.003	0.85	8.6	0.03	3900	0.74
23-Apr-97	0.01	10	100	6.3	276	0	0.2	20	20	20	0.017	0.002	0.74	0.003	0.74	8.5	0.03	100	0.72
30-Apr-97	0.052	10	310	25.2	223	0	0	10	10	10	0.06	0.002	0.45	0.003	0.45	8.5	0.03	310	0.95
07-May-97	0.077	40	240	18.4	249	0	0	200	200	200	0.083	0.003	0.83	0.003	0.83	8.2	0.03	240	1.12
14-May-97	0.028	10	800	19.7	240	0	0	10	10	10	0.047	0.002	0.67	0.003	0.67	8.3	0.03	800	0.53
21-May-97	0.024	10	110	10.9	284	0	0.2	60	60	60	0.035	0.004	0.49	0.003	0.49	8.4	0.03	110	0.3
28-May-97	0.011	20	260	10.7	279	0	0	40	40	40	0.013	0.002	0.54	0.003	0.54	8.5	0.03	260	0.42
04-Jun-97	0.011	10	300	7.9	283	0	0	120	120	120	0.013	0.002	0.73	0.003	0.73	8.5	0.03	300	0.46
11-Jun-97	0.011	10	2600	7.9	275	0	0.2	680	680	260	0.011	0.002	1.06	0.003	1.07	8.3	0.03	2600	0.62
18-Jun-97	0.011	10	140	16.7	260	0	0	130	130	130	0.025	0.002	0.43	0.003	0.43	8.8	0.03	140	1.41
25-Jun-97	0.032	10	640	22	261	0	0	270	270	30	0.076	0.005	0.54	0.003	0.54	8.9	0.03	640	1.72
02-Jul-97	0.022	10	500	13.2	318	0	0	370	370	40	0.053	0.002	0.66	0.003	0.66	8.4	0.03	500	0.6
09-Jul-97	0.017	10	250	11.7	269	0	0	130	130	130	0.017	0.002	0.36	0.003	0.37	8.4	0.03	250	0.2
16-Jul-97	0.011	10	800	11.7	269	0	0.2	320	320	320	0.016	0.002	0.23	0.003	0.23	8.6	0.03	800	0.43
23-Jul-97	0.011	10	100	12.9	289	0	0	90	90	90	0.018	0.002	0.75	0.003	0.75	8.4	0.03	100	0.47
30-Jul-97	0.07	30	2080	52.4	250	0	0	1220	1220	220	0.147	0.004	0.53	0.003	0.53	7.9	0.03	2080	1.36

Site Number 2									
Date	Triadimefon	Triallate	Triazophos	Triclopyr	Trietazine	Trifluralin	Turbidity		
23-Oct-96	0.02	0.02	0.03		0.02		0.78		
30-Oct-96							0.74		
06-Nov-96							4		
13-Nov-96							0.94		
20-Nov-96	0.02	0.02	0.03		0.02		0.55		
27-Nov-96							0.64		
04-Dec-96							1.53		
11-Dec-96							0.56		
18-Dec-96							1.28		
03-Jan-97							0.64		
08-Jan-97							0.28		
15-Jan-97							0.47		
22-Jan-97							0.63		
29-Jan-97							0.81		
06-Feb-97							1.14		
12-Feb-97							5.8		
26-Feb-97							2.64		
05-Mar-97							0.31		
12-Mar-97							1.89		
19-Mar-97							2.94		
26-Mar-97							0.86		
02-Apr-97							0.45		
07-Apr-97							0.62		
16-Apr-97	0.02	0.02	0.03	0.02	0.02	0.01	0.5		
23-Apr-97							0.94		
30-Apr-97							1.67		
07-May-97							0.72		
14-May-97	0.02	0.02	0.03	0.02	0.02	0.01	0.57		
21-May-97							0.22		
28-May-97							0.44		
04-Jun-97							0.46		
11-Jun-97	0.02	0.02	0.03	0.02	0.02	0.01	1.18		
18-Jun-97							0.44		
25-Jun-97							0.58		
02-Jul-97							0.49		
09-Jul-97	0.02	0.02	0.03	0.02	0.02	0.01	0.2		
16-Jul-97							0.42		
23-Jul-97							0.5		
30-Jul-97							0.93		

Sample site 3	River Wharfe us of confluence with River Skirfare																	
Date	2,4 - 2,4 - D	DB	2,4,5 - T	2,4,6 - TCP	2,4-dichlorophenol	2,6-dichlorophenol	2-chlorophenol	4-chlorophenol	Atrrin	Aluminium	Atrazine	Azinphos-methyl	Bentazone	Biphenox	BOD (total)	Bromoxynil	Carbendazim	Carbetamide
23-Oct-96				0.1	0.1	0.1	0.1	0.1	0.1	0.049	0.02	0.02		0.02	1.33			
30-Oct-96				0.1	0.1	0.1	0.1	0.1	0.1	0.058					2.37			
06-Nov-96				0.1	0.1	0.1	0.1	0.1	0.1	0.576					1.43			
13-Nov-96				0.1	0.1	0.1	0.1	0.1	0.1	0.052					0			
20-Nov-96				0.1	0.1	0.1	0.1	0.1	0.1	0.051					0			
27-Nov-96				0.1	0.1	0.1	0.1	0.1	0.1	0.059	0.02	0.02		0.02	0			
04-Dec-96				0.1	0.1	0.1	0.1	0.1	0.1	0.124					0			
11-Dec-96				0.1	0.1	0.1	0.1	0.1	0.1	0.027					0			
18-Dec-96				0.1	0.1	0.1	0.1	0.1	0.1	0.058					0			
03-Jan-97				0.1	0.1	0.1	0.1	0.1	0.1	0.01					0			
08-Jan-97				0.1	0.1	0.1	0.1	0.1	0.1	0.024					0			
15-Jan-97				0.1	0.1	0.1	0.1	0.1	0.1	0.059					0			
22-Jan-97				0.1	0.1	0.1	0.1	0.1	0.1	0.042					0			
28-Jan-97				0.1	0.1	0.1	0.1	0.1	0.1	0.034					0			
06-Feb-97				0.1	0.1	0.1	0.1	0.1	0.1	0.067					0			
12-Feb-97				0.1	0.1	0.1	0.1	0.1	0.1	0.384					0			
26-Feb-97				0.1	0.1	0.1	0.1	0.1	0.1	0.13					0			
06-Mar-97				0.1	0.1	0.1	0.1	0.1	0.1	0.041					0			
12-Mar-97				0.1	0.1	0.1	0.1	0.1	0.1	0.058					0			
19-Mar-97				0.1	0.1	0.1	0.1	0.1	0.1	0.294					0			
26-Mar-97				0.1	0.1	0.1	0.1	0.1	0.1	0.127					0			
02-Apr-97				0.1	0.1	0.1	0.1	0.1	0.1	0.033					0			
07-Apr-97				0.1	0.1	0.1	0.1	0.1	0.1	0.019					0			
16-Apr-97			0.02	0.02	0.1	0.1	0.1	0.1	0.1	0.91					1.4			
23-Apr-97			0.02	0.02	0.1	0.1	0.1	0.1	0.1	0.01	0.02	0.02	0.02	0.02	1.4	0.02	0.04	0.03
30-Apr-97				0.1	0.1	0.1	0.1	0.1	0.1	0.046					1.4			
07-May-97				0.1	0.1	0.1	0.1	0.1	0.1	0.078					1.4			
14-May-97				0.1	0.1	0.1	0.1	0.1	0.1	0.064					1.4			
21-May-97		0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.037	0.02	0.02	0.02	0.02	0.7	0.02	0.04	0.03
28-May-97				0.1	0.1	0.1	0.1	0.1	0.1	0.019					0.7			
04-Jun-97				0.1	0.1	0.1	0.1	0.1	0.1	0.028					1.4			
11-Jun-97				0.1	0.1	0.1	0.1	0.1	0.1	0.029					1.9			
18-Jun-97		0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.013	0.02	0.02	0.02	0.02	0	0.02	0.04	0.03
25-Jun-97				0.1	0.1	0.1	0.1	0.1	0.1	0.042					0			
02-Jul-97				0.1	0.1	0.1	0.1	0.1	0.1	0.05					0			
09-Jul-97				0.1	0.1	0.1	0.1	0.1	0.1	0.026					1.4			
16-Jul-97			0.02	0.04	0.1	0.1	0.1	0.1	0.1	0.026					1.4			
23-Jul-97			0.02	0.04	0.1	0.1	0.1	0.1	0.1	0.005	0.02	0.02	0.02	0.02	0	0.02	0.04	0.03
30-Jul-97				0.1	0.1	0.1	0.1	0.1	0.1	0.023					1.4			
				0.1	0.1	0.1	0.1	0.1	0.1	0.037					1.9			

Sample site 3														
Date	Carbophenothion	Chlordane	Chlorfenvinphos	Chloridazon	Chlorothalonil	Chlorotaluron	Chlorpropham	Chlorpyrifos	Clopyralid	Clostridium Perfringens	Goliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	Cyanazine
23-Oct-96										10	1200	31.4	266	
30-Oct-96	0.02		0.03					0.03		20	350	36	258	0.03
06-Nov-96										210	2880	47.5	169	
13-Nov-96										20	170	24	242	
20-Nov-96										140	720	16.6	262	
27-Nov-96	0.02		0.03					0.03		110	150	23.5	239	0.03
04-Dec-96										30	300	27.3	199	
11-Dec-96										20	530	17.7	255	
18-Dec-96										150	720	27.9	210	
03-Jan-97										20	1400	11.5	273	
08-Jan-97										30	820	10	316	
15-Jan-97										20	200	20.1	204	
22-Jan-97										200	1100	15.6	266	
29-Jan-97										8	120	17.2	241	
06-Feb-97										40	370	20.4	221	
12-Feb-97										100	960	46.5	137	
26-Feb-97										50	14	25.9	173	
05-Mar-97										30	120	14.2	261	
12-Mar-97										30	130	12.4	270	
19-Mar-97										30	820	56.8	143	
26-Mar-97										90	1160	43.1	181	
02-Apr-97										60	1620	12.8	265	
07-Apr-97										10	840	11.5	273	
16-Apr-97										20	150	9.1	273	
23-Apr-97	0.02	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	50	100	6.4	301	0.03
30-Apr-97										10	200	28.2	217	
07-May-97										20	1040	28.5	237	
14-May-97										30	4000	29	226	
21-May-97	0.02	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	20	420	25.6	251	0.03
28-May-97										20	130	11.9	263	
04-Jun-97										40	210	9.9	284	
11-Jun-97										190	11000	14.6	277	
18-Jun-97	0.02	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	70	1000	19.4	263	0.03
25-Jun-97										60	2120	32	246	
02-Jul-97										19	3000	20.4	204	
09-Jul-97										20	18000	14.6	260	
26-Jul-97			0.03	0.02	0.01	0.02	0.04	0.03	0.02	170	13400	15	273	0.03
23-Jul-97	0.02	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	90	420	11.3	295	
30-Jul-97										20	1960	33.5	255	

Sample site 3																	
Date	Desmetryne	Diazinon	Dicamba	Dichlobenil	Dichlorop	Dichlorvos	Dieldrin	Dimethoate	Diazin	E. Coli	Endosulphian Alpha	Endosulphian Beta	Endrin	EPTC	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci
23-Oct-96															310	310	110
30-Oct-96	0.02	0.02		0.04		0.02		0.02						0.03	240	240	140
06-Nov-96															1960	1960	1780
13-Nov-96															60	60	30
20-Nov-96															720	720	810
27-Nov-96	0.02	0.02		0.04		0.02		0.02						0.03	80	80	100
04-Dec-96															120	120	120
11-Dec-96															360	360	20
18-Dec-96															480	480	180
03-Jan-97															900	900	370
08-Jan-97															460	460	60
15-Jan-97															90	90	60
22-Jan-97															760	760	290
29-Jan-97															85	85	11
06-Feb-97															130	130	40
12-Feb-97															270	270	50
26-Feb-97															11	11	100
05-Mar-97															70	70	20
12-Mar-97															220	220	50
19-Mar-97															110	110	60
26-Mar-97															90	90	60
02-Apr-97															280	280	10
07-Apr-97															80	80	50
16-Apr-97															30	30	30
23-Apr-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0.02	0.01	0.01	0.02	0.03	40	40	10
30-Apr-97															30	30	10
07-May-97															830	830	200
14-May-97															70	70	20
21-May-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0.02	0.01	0.01	0.02	0.03	290	290	90
28-May-97															10	10	10
04-Jun-97															140	140	110
11-Jun-97															6200	6200	1020
18-Jun-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0.02	0.01	0.01	0.02	0.03	320	320	100
25-Jun-97															980	980	210
02-Jul-97															1120	1120	100
09-Jul-97															1400	1400	1420
16-Jul-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0.02	0.01	0.01	0.02	0.03	420	420	70
23-Jul-97															250	250	80
30-Jul-97															720	720	330

Date	Iprodione	Iron (total)	Isodrin	Isoproturon	Linuron	Malathion	Manganese (total)	MCPA	MCPB	MCPP	M-cresol	Methoxychlor	Monuron	Nitrate	Nitrite	Nitrogen - total oxidised	O-cresol	OP - DDT	Oxadixyl	Parathion
23-Oct-96		0.103					0.005				0.1			0.97	0.003	0.97	0.1			
30-Oct-96	0.02	0.13				0.02	0.007							1.18	0.003	1.19	0.1		0.03	0.02
06-Nov-96		0.438					0.019							0.69	0.008	0.69	0.1			
13-Nov-96		0.094					0.007							1.05	0.003	1.05	0.1			
20-Nov-96		0.098					0.011							1.11	0.003	1.12	0.1			
27-Nov-96	0.02	0.1				0.02	0.006							1.1	0.003	1.1	0.1		0.03	0.02
04-Dec-96		0.128					0.007							0.84	0.003	0.84	0.1			
11-Dec-96		0.067					0.006							1.26	0.003	1.26	0.1			
18-Dec-96		0.12					0.005							0.95	0.003	0.95	0.1			
03-Jan-97		0.033					0.003							1.09	0.003	1.09	0.1			
08-Jan-97		0.061					0.012							1.19	0.003	1.19	0.1			
15-Jan-97		0.081					0.003							1.08	0.003	1.09	0.1			
22-Jan-97		0.06					0.006							1.39	0.003	1.39	0.1			
29-Jan-97		0.075					0.005							0.9	0.003	0.91	0.1			
06-Feb-97		0.093					0.005							1.05	0.003	1.05	0.1			
12-Feb-97		0.322					0.014							3.58	0.005	3.58	0.1			
26-Feb-97		0.127					0.006							0.63	0.003	0.63	0.1			
05-Mar-97		0.069					0.007							1.04	0.003	1.04	0.1			
12-Mar-97		0.055					0.007							1.02	0.003	1.02	0.1			
19-Mar-97		0.338					0.008							3.68	0.004	3.68	0.1			
26-Mar-97		0.255					0.008							0.42	0.003	0.43	0.1			
02-Apr-97		0.058					0.004							0.79	0.003	0.8	0.1			
07-Apr-97		0.05					0.003							0.76	0.003	0.76	0.1			
16-Apr-97		0.171					0.006							0.82	0.003	0.82	0.1			
23-Apr-97	0.02	0.026	0.005	0.01	0.02	0.02	0.002	0.03	0.04	0.02	0.1	0.01	0.02	0.99	0.003	0.99	0.1	0.01	0.03	0.02
30-Apr-97		0.066					0.002							0.56	0.003	0.56	0.1			
07-May-97		0.105					0.007							0.57	0.003	0.57	0.1			
14-May-97		0.109					0.004							0.5	0.003	0.5	0.1			
21-May-97	0.02	0.092	0.005	0.01	0.02	0.02	0.004	0.03	0.04	0.02	0.1	0.01	0.02	0.39	0.003	0.39	0.1	0.01	0.03	0.02
28-May-97		0.047					0.003							0.6	0.003	0.6	0.1			
04-Jun-97		0.033					0.007							0.53	0.005	0.64	0.1			
11-Jun-97		0.042					0.013							1.11	0.01	1.12	0.1			
18-Jun-97	0.02	0.064	0.005	0.01	0.02	0.02	0.012	0.03	0.04	0.02	0.1	0.01	0.02	0.6	0.005	0.6	0.1	0.01	0.03	0.02
25-Jun-97		0.116					0.017							0.57	0.007	0.57	0.1			
02-Jul-97		0.114					0.009							0.49	0.003	0.5	0.1			
09-Jul-97		0.077					0.014							0.52	0.006	0.53	0.1			
16-Jul-97	0.02	0.066	0.005	0.01	0.02	0.02	0.01	0.03	0.04	0.02	0.1	0.01	0.02	0.58	0.005	0.59	0.1	0.01	0.03	0.02
23-Jul-97		0.054					0.008							0.45	0.003	0.46	0.1			
30-Jul-97		0.119					0.008							0.39	0.004	0.4	0.1			

Sample site 3													
Date	TDE (pp)	Tecnazene	Terbutylazine	Terbutryne	Total Ammonia	Total Coliforms	Triadimefon	Triallate	Triazophos	Triclopyr	Trietazine	Trifluralin	Turbidity
28-Oct-96					0.03	1200							0.64
30-Oct-96			0.02	0.02	0.03	360	0.02	0.02	0.03		0.02		1.23
06-Nov-96					0.03	2880							7.3
13-Nov-96					0.03	170							1.07
20-Nov-96					0.03	720							0.95
27-Nov-96				0.02	0.03	150	0.02	0.02	0.03		0.02		0.97
04-Dec-96					0.03	300							2.66
11-Dec-96					0.03	530							0.58
18-Dec-96					0.03	720							1.09
03-Jan-97					0.03	1400							0.41
08-Jan-97					0.03	820							0.63
15-Jan-97					0.03	200							0.9
22-Jan-97					0.03	1100							1.25
29-Jan-97					0.03	120							1.25
06-Feb-97					0.03	370							1.86
12-Feb-97					0.03	960							8.4
26-Feb-97					0.03	14							3.01
05-Mar-97					0.03	120							0.83
12-Mar-97					0.03	130							0.9
19-Mar-97					0.03	820							3.5
26-Mar-97					0.03	1160							1.24
02-Apr-97					0.03	1620							0.58
07-Apr-97					0.03	840							2.03
16-Apr-97					0.03	150							1.27
23-Apr-97	0.01	0.01		0.02	0.03	100	0.02	0.02	0.03	0.02	0.02	0.01	1.55
30-Apr-97					0.03	290							0.77
07-May-97					0.03	1040							1.43
14-May-97					0.03	4000							1.23
21-May-97	0.01	0.01		0.02	0.03	420	0.02	0.02	0.03	0.02	0.02	0.01	0.94
28-May-97					0.03	130							0.66
04-Jun-97					0.03	210							2
11-Jun-97					0.03	11000							0.67
18-Jun-97	0.01	0.01		0.02	0.03	1000	0.02	0.02	0.03	0.02	0.02	0.01	1.57
25-Jun-97					0.03	2120							0.74
02-Jul-97					0.03	3600							0.41
09-Jul-97					0.03	18000							0.98
16-Jul-97	0.01	0.01		0.02	0.03	1340	0.02	0.02	0.03	0.02	0.02	0.01	0.84
23-Jul-97					0.03	420							0.89
30-Jul-97					0.03	1980							0.89

Sample Site 4
Captain Best & Union Bridges

Date	Aluminium	Cleistidium Perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	E. Coli	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	Oil & Grease - Total	pH	Total Ammonia	Total Coliforms	Turbidity
25-Oct-98	0.054	20	0	1170	358	0	120	120	10	0.101	0.008	2.26	0.007	2.27	2.27	8.2	0.03	1170	1.35
30-Oct-98	0.04	70	6000	23.1	347	0	2600	2600	2920	0.122	0.011	2.64	0.009	2.65	0.06	8.2	0.03	9000	3.85
06-Nov-98	0.07	450	10000	28.8	556	0	2890	2890	16000	0.597	0.053	2.46	0.018	2.48	0.06	7.7	0.03	10000	10.4
13-Nov-98	0.07	100	310	18.4	343	0	210	210	710	0.125	0.03	3.21	0.012	3.23	0.04	8.1	0.03	310	2.26
20-Nov-98	0.219	180	8000	28.1	422	0	4000	4000	600	0.318	0.038	2.57	0.027	2.6	0.07	8.3	0.03	8000	7.5
27-Nov-98	0.745	40	80	18.3	349	0	10	10	190	0.112	0.016	3.3	0.016	3.32	0.03	8.1	0.03	80	2.36
04-Dec-98	0.174	60	300	28	296	0	90	90	160	0.172	0.016	2.55	0.013	2.56	0.03	7.8	0.03	300	4.9
11-Dec-98	0.057	10	10	1700	369	0	10	10	60	0.06	0.011	4.1	0.013	4.32	0.03	8	0.03	170	0.9
18-Dec-98	0.037	90	10	173	351	0	70	70	60	0.116	0.013	2.96	0.01	2.97	0.04	8	0.03	170	2.39
03-Jan-97	0.01	0	0	169	352	0	120	120	70	0.026	0.003	3.92	0.039	3.96	0.03	8.2	0.03	150	1.4
08-Jan-97	0.039	30	1690	10.2	352	0	320	320	40	0.085	0.008	3.2	0.024	3.52	0.03	8.2	0.03	1690	1.14
15-Jan-97	0.026	5	40	16.5	342	0	40	40	10	0.064	0.005	2.68	0.057	2.86	0.03	8.1	0.03	40	0.84
22-Jan-97	0.026	30	1320	14.9	479	0	46	46	46	0.063	0.004	3	0.007	3.01	0.03	8.3	0.03	1320	1.74
29-Jan-97	0.063	9	20	10.7	363	0	28	28	28	0.075	0.003	2.68	0.004	2.69	0.03	8.3	0.03	20	1.86
05-Feb-97	0.068	200	620	18.7	326	0	50	50	70	0.12	0.009	2.48	0.008	2.49	0.03	8.2	0.03	620	2.86
12-Feb-97	1.47	7000	457	10	218	0	960	960	350	1.54	0.02	3.31	0.002	3.31	0.03	7.7	0.04	3000	150
19-Feb-97	0.391	180	16	31.9	245	0	16	16	410	0.289	0.026	2.63	0.013	2.66	0.03	7.9	0.03	160	1.3
06-Mar-97	0.048	10	150	13.2	350	0	10	10	20	0.071	0.001	3.81	0.014	3.89	0.03	8.2	0.03	200	0.77
12-Mar-97	0.03	10	300	9.3	367	0	50	50	70	0.07	0.006	3.85	0.011	3.96	0.03	8.3	0.03	300	3.27
19-Mar-97	0.112	70	560	27.7	295	0	210	210	80	0.179	0.011	3.02	0.01	3.03	0.03	8.2	0.03	560	3.63
26-Mar-97	0.107	10	260	15	316	0	130	130	10	0.08	0.011	2.46	0.011	2.47	0.03	8.4	0.03	260	1.23
02-Apr-97	0.023	90	640	12.8	345	0	160	160	10	0.06	0.005	2.88	0.004	2.88	0.03	8.5	0.03	640	1.23
07-Apr-97	0.022	90	720	9.5	343	0	160	160	97	0.074	0.003	2.97	0.004	2.97	0.03	8.4	0.03	720	1.52
14-Apr-97	0.02	90	10	7.4	338	10	110	110	20	0.06	0.003	3.26	0.003	3.29	0.03	8.5	0.03	10	0.82
21-Apr-97	0.01	60	368	6.8	348	0	50	50	40	0.044	0.002	2.91	0.003	2.91	0.03	8.6	0.03	90	0.96
30-Apr-97	0.048	20	490	19.3	326	0	229	229	80	0.124	0.008	1.94	0.003	1.94	0.03	8.5	0.03	490	0.81
07-May-97	0.015	70	320	25.4	340	0	1690	1690	310	0.121	0.011	2.2	0.022	2.22	0.03	8.1	0.03	2920	1.54
14-May-97	0.05	70	4600	24.2	306	0	270	270	100	0.175	0.012	1.76	0.005	1.76	0.03	8	0.03	4600	1.85
21-May-97	0.047	50	960	26.6	327	0	520	520	50	0.155	0.006	2.33	0.004	2.34	0.03	8.5	0.03	960	1.26
06-Jun-97	0.013	20	1800	10.1	354	0	450	450	10	0.083	0.003	3.04	0.007	3.04	0.03	8.5	0.03	1870	0.72
13-Jun-97	0.018	90	340	8	311	0	30000	30000	4940	0.229	0.028	2.34	0.018	2.35	0.04	7.6	0.03	66000	4.6
19-Jun-97	0.036	50	5000	22.8	311	0	890	890	190	0.176	0.006	2.63	0.006	2.63	0.03	8.5	0.03	1200	0.46
26-Jun-97	0.019	60	1200	11	351	0	1460	1460	140	0.107	0.005	2.7	0.008	2.72	0.04	8.2	0.03	2720	1.82
02-Jul-97	0.019	20	2720	18.3	376	0	2400	2400	10	0.065	0.005	2.4	0.015	2.42	0.03	8.3	0.03	3000	0.63
09-Jul-97	0.052	50	7500	19.3	380	0	4000	4000	310	0.096	0.011	1.96	0.031	1.98	0.03	8.1	0.03	7900	0.65
16-Jul-97	0.016	30	1780	14.8	402	0	680	680	170	0.134	0.006	1.86	0.015	1.9	0.03	8.2	0.03	1780	0.52
23-Jul-97	0.014	60	2600	10.9	368	0	510	510	170	0.083	0.005	2.3	0.003	2.31	0.005	8.3	0.03	2670	0.69
30-Jul-97	0.011	480	3760	11.8	348	0	450	450	110	0.101	0.001	1.71	0.005	1.75	0.03	8.5	0.03	3760	1.26

Sample site 5		River Wharfe @ Burnesall Bridge																	
Date	Aluminium	BOD (total)	Clostridium Perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	E. Coli	Faecal Coliforms	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	Oil & Grease - Total	pH	Total Ammonia	Total Coliforms	Turbidity
26-Oct-96	0.654	1.33	20	2000	34.5	278	390	120	0.14	0.005	1.5	0.003	1.5	0.003	8.3	0.03	2000	1.22	
30-Oct-96	0.559	2.37	40	510	32.5	264	360	340	0.136	0.006	1.81	0.004	1.82	0.003	8.3	0.03	510	1.44	
06-Nov-96	0.188	2.09	330	2440	51	186	2160	2160	0.674	0.061	1.13	0.008	1.14	0.008	7.8	0.03	2440	11.9	
13-Nov-96	0.053	0	160	850	29.8	269	410	410	0.124	0.007	1.62	0.003	1.62	0.003	8.2	0.03	860	1.75	
20-Nov-96	0.102	0	27	1840	27	307	1000	170	0.127	0.011	2.25	0.007	2.26	0.003	8.1	0.03	1840	2.78	
27-Nov-96	0.033	0	90	700	25	285	180	60	0.14	0.007	1.93	0.003	1.93	0.003	8.1	0.03	500	1.37	
04-Dec-96	0.137	0	96	400	36.2	220	340	140	0.139	0.004	1.94	0.004	1.94	0.004	8.0	0.03	700	3.18	
11-Dec-96	0.032	0	145	570	10.8	301	440	440	0.05	0.004	2.44	0.003	2.44	0.003	8.1	0.03	570	0.59	
19-Dec-96	0.05	0	100	490	20.8	265	220	176	0.004	0.004	1.75	0.005	1.76	0.004	8.0	0.03	460	1.1	
09-Jan-97	0.01	0	210	650	10.4	315	440	440	0.01	0.002	2.03	0.006	2.03	0.002	8.2	0.03	650	1.65	
09-Jan-97	0.028	0	90	940	9.6	327	320	320	0.044	0.003	2.07	0.003	2.07	0.003	8.2	0.03	940	0.52	
15-Jan-97	0.055	0	19	300	19.1	240	270	200	0.081	0.003	1.39	0.004	1.4	0.003	8.0	0.03	300	1.22	
22-Jan-97	0.015	0	70	220	15.4	285	100	100	0.003	0.004	1.7	0.003	1.7	0.003	8.3	0.03	220	1.69	
23-Jan-97	0.028	0	6	15	15	269	14	3	0.057	0.003	1.46	0.004	1.47	0.004	8.2	0.03	15	1.5	
06-Feb-97	0.091	0	70	380	22.4	240	210	210	0.083	0.004	1.58	0.003	1.58	0.003	8.2	0.03	380	2.83	
12-Feb-97	0.441	0	470	2000	51.2	154	1690	180	0.421	0.026	3.49	0.005	3.49	0.005	8.1	0.03	2000	12.8	
26-Feb-97	0.123	0	300	152	28.8	211	88	88	0.125	0.007	1.22	0.003	1.22	0.003	8.1	0.03	152	4.89	
05-Mar-97	0.045	0	40	260	14.7	266	100	20	0.081	0.006	2.12	0.003	2.12	0.003	8.2	0.03	260	1.29	
12-Mar-97	0.028	0	10	300	9.9	506	210	210	0.043	0.004	1.97	0.003	1.97	0.003	8.4	0.03	300	0.65	
19-Mar-97	0.255	0	60	570	45.8	180	200	120	0.288	0.009	3.53	0.004	3.53	0.004	8.6	0.03	570	3.3	
26-Mar-97	0.045	0	10	280	24.3	238	80	30	0.082	0.003	1.03	0.005	1.03	0.003	8.6	0.03	280	1.24	
02-Apr-97	0.025	0	50	600	15.6	290	60	60	0.04	0.003	1.35	0.004	1.36	0.003	8.5	0.03	600	0.7	
07-Apr-97	0.02	0	100	550	11.3	365	340	10	0.025	0.004	1.78	0.012	1.79	0.003	8.5	0.03	550	0.94	
16-Apr-97	0.021	1.4	40	340	8.9	506	70	70	0.022	0.003	1.64	0.012	1.65	0.003	8.5	0.03	340	0.57	
23-Apr-97	0.01	2	40	40	8	328	70	70	0.022	0.003	1.64	0.012	1.65	0.003	8.5	0.03	40	1.05	
30-Apr-97	0.067	1.4	50	560	31.5	229	240	240	0.104	0.004	0.78	0.005	0.78	0.003	8.4	0.03	560	3.6	
07-May-97	0.103	1.4	60	1440	30.8	265	1400	1400	0.104	0.004	1.09	0.005	1.1	0.003	8.1	0.03	1440	2.4	
14-May-97	0.073	1.4	70	500	36.8	203	280	280	0.127	0.009	1.22	0.004	1.22	0.003	8.1	0.03	500	4.00	
21-May-97	0.024	0.7	40	370	8.7	301	150	150	0.051	0.004	1.49	0.008	1.5	0.004	8.6	0.03	370	0.54	
28-May-97	0.015	0.7	30	250	12.3	311	70	70	0.028	0.005	1.53	0.015	1.55	0.003	8.5	0.03	250	0.64	
04-Jun-97	0.013	1.4	50	290	9.4	314	70	70	0.028	0.005	1.44	0.017	1.46	0.003	8.0	0.03	290	0.78	
11-Jun-97	0.038	1.8	60	6500	14.6	315	5400	3160	0.052	0.006	1.03	0.012	1.04	0.003	8.6	0.03	6500	2.1	
18-Jun-97	0.018	0	80	1040	19.2	282	310	60	0.052	0.006	1.03	0.012	1.04	0.003	8.6	0.03	1040	0.72	
25-Jun-97	0.034	0	40	760	24.7	270	320	320	0.13	0.009	1.1	0.008	1.1	0.003	8.2	0.03	760	1.2	
02-Jul-97	0.053	1.4	20	11000	26.6	264	5900	110	0.14	0.008	0.81	0.005	0.81	0.003	8.2	0.03	11000	0.95	
09-Jul-97	0.051	1.4	120	6000	20.7	319	2000	280	0.092	0.018	1.16	0.012	1.18	0.003	8.1	0.03	6000	0.7	
16-Jul-97	0.033	0	30	1480	13.1	322	700	700	0.07	0.018	1.06	0.01	1.06	0.003	8.4	0.03	1480	0.43	
30-Jul-97	0.019	0	40	370	15.1	317	160	60	0.06	0.01	1.16	0.012	1.16	0.003	8.3	0.03	370	0.16	
30-Jul-97	0.0211	2.1	10	1560	29.4	258	410	100	0.081	0.008	0.98	0.011	0.97	0.003	8.2	0.03	1560	0.78	

Sample site 6	River Dlibb @ Hartington														
Date	Parameter 2,4,6 - TCP	2,4-dichlorophenol	2,6-dichlorophenol	2-chlorophenol	4-chlorophenol	Aluminium	Clostridium Perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	E. Coli	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)
23-Oct-96	0.1	0.1	0.1	0.1	0.1	0.116	30	320	54.4	237	0	200	200	20	0.377
30-Oct-96	0.1	0.1	0.1	0.1	0.1	0.127	20	150	51.7	232	0	70	70	10	0.407
06-Nov-96	0.1	0.1	0.1	0.1	0.1	0.078	400	2280	90.9	205	0	1560	1560	190	0.876
13-Nov-96	0.1	0.1	0.1	0.1	0.1	0.188	10	940	57.4	217	0	110	110	20	0.42
20-Nov-96	0.1	0.1	0.1	0.1	0.1	0.453	540	6000	65	226	0	4500	4500	390	0.523
27-Nov-96	0.1	0.1	0.1	0.1	0.1	0.238	80	600	48.5	205	0	140	140	40	0.441
04-Dec-96	0.1	0.1	0.1	0.1	0.1	0.264	60	2000	77.7	205	0	130	130	60	0.366
11-Dec-96	0.1	0.1	0.1	0.1	0.1	0.144	20	460	73.4	207	0	0	0	10	0.369
18-Dec-96	0.1	0.1	0.1	0.1	0.1	0.299	150	640	51.7	224	0	270	270	40	0.615
03-Jan-97	0.1	0.1	0.1	0.1	0.1	0.015	10	180	54.2	228	0	40	40	0	0.031
08-Jan-97	0.1	0.1	0.1	0.1	0.1	0.466	30	1460	103	121	0	0	0	10	0.779
15-Jan-97	0.1	0.1	0.1	0.1	0.1	0.073	10	300	28.1	268	0	10	10	10	0.148
22-Jan-97	0.1	0.1	0.1	0.1	0.1	0.487	10	440	131	97	0	40	40	10	0.819
29-Jan-97	0.1	0.1	0.1	0.1	0.1	0.475	2	3	118	88	0	1	1	0	0.807
06-Feb-97	0.1	0.1	0.1	0.1	0.1	0.141	370	230	32.5	253	0	150	150	960	0.253
12-Feb-97	0.1	0.1	0.1	0.1	0.1	1.1	1400	5000	90	184	0	1400	1400	2000	1.43
26-Feb-97	0.1	0.1	0.1	0.1	0.1	0.443	50	46	105	96	0	28	28	100	0.766
05-Mar-97	0.1	0.1	0.1	0.1	0.1	0.387	10	680	100	136	0	50	50	40	0.624
12-Mar-97	0.1	0.1	0.1	0.1	0.1	0.263	10	210	81.6	163	0	60	60	10	0.507
19-Mar-97	0.1	0.1	0.1	0.1	0.1	0.41	90	830	4.1	105	0	280	280	290	0.716
26-Mar-97	0.1	0.1	0.1	0.1	0.1	0.33	60	500	94.5	117	0	50	50	20	0.652
02-Apr-97	0.1	0.1	0.1	0.1	0.1	0.225	30	1640	77	170	0	10	10	10	0.461
07-Apr-97	0.1	0.1	0.1	0.1	0.1	0.305	30	520	74.4	173	0	80	80	10	0.637
16-Apr-97	0.1	0.1	0.1	0.1	0.1	0.358	10	430	116	76	0	70	70	0	0.7
23-Apr-97	0.1	0.1	0.1	0.1	0.1	0.341	20	60	108	74	0	20	20	10	0.678
30-Apr-97	0.1	0.1	0.1	0.1	0.1	0.169	40	1220	34.5	258	0	150	150	80	0.47
07-May-97	0.1	0.1	0.1	0.1	0.1	0.144	100	2760	47.2	264	0	1320	1320	270	0.245
14-May-97	0.1	0.1	0.1	0.1	0.1	0.204	60	3800	65.6	231	0	480	480	260	0.394
21-May-97	0.1	0.1	0.1	0.1	0.1	0.078	50	250	42.3	278	0	350	350	50	0.228
28-May-97	0.1	0.1	0.1	0.1	0.1	0.293	20	230	117	78	0	130	130	50	0.645
04-Jun-97	0.1	0.1	0.1	0.1	0.1	0.309	10	50	19.4	78	0	50	50	0	0.666
11-Jun-97	0.1	0.1	0.1	0.1	0.1	0.367	30	4500	107	93	0	3400	3400	760	0.701
18-Jun-97	0.1	0.1	0.1	0.1	0.1	0.323	10	1880	114	83	0	1480	1480	70	0.71
25-Jun-97	0.1	0.1	0.1	0.1	0.1	0.262	10	160	91.4	90	0	140	140	90	0.626
02-Jul-97	0.1	0.1	0.1	0.1	0.1	0.11	20	1800	36.7	264	0	1000	1000	170	0.314
09-Jul-97	0.1	0.1	0.1	0.1	0.1	0.302	10	250	103	82	0	180	180	30	0.767
16-Jul-97	0.1	0.1	0.1	0.1	0.1	0.268	10	900	111	100	0	160	160	10	0.658
23-Jul-97	0.1	0.1	0.1	0.1	0.1	0.284	10	250	115	80	0	90	90	80	0.687
30-Jul-97	0.1	0.1	0.1	0.1	0.1	0.302	10	140	108	89	0	100	100	80	0.693

Sample site 6		Manganese (total)	M-cresol	Nitrate	Nitrite	Nitrogen - total oxidised	O-cresol	P-cresol	Pentachlorophenol	pH	Phenol	Total Ammonia	Total Coliforms	Turbidity
23-Oct-96	0.067	0.1	1.58	0.003	1.59	0.1	0.1	0.1	0.1	8.1	0.1	0.03	300	1.71
30-Oct-96	0.062	0.1	1.6	0.004	1.6	0.1	0.1	0.1	0.1	7.9	0.1	0.03	150	1.58
06-Nov-96	0.076	0.1	2.21	0.012	2.22	0.1	0.1	0.1	0.1	7.7	0.1	0.03	2260	10.7
13-Nov-96	0.044	0.1	1.59	0.004	1.59	0.1	0.1	0.1	0.1	8.1	0.1	0.03	940	2.37
20-Nov-96	0.065	0.1	1.43	0.012	1.44	0.1	0.1	0.1	0.1	7.8	0.1	0.03	6000	6.9
27-Nov-96	0.05	0.1	2.13	0.004	2.14	0.1	0.1	0.1	0.1	8.1	0.1	0.03	600	2.32
04-Dec-96	0.032	0.1	1.72	0.007	1.73	0.1	0.1	0.1	0.1	7.8	0.1	0.03	2000	3.56
11-Dec-96	0.043	0.1	1.57	0.003	1.57	0.1	0.1	0.1	0.1	7.9	0.1	0.03	460	2.28
18-Dec-96	0.215	0.1	1.35	0.004	1.35	0.1	0.1	0.1	0.1	7.8	0.1	0.03	640	7.1
03-Jan-97	0.003	0.1	1.45	0.003	1.46	0.1	0.1	0.1	0.1	8.1	0.1	0.03	180	2.3
08-Jan-97	0.067	0.1	0.87	0.006	0.88	0.1	0.1	0.1	0.1	7.7	0.1	0.03	1460	5.6
15-Jan-97	0.043	0.1	1.66	0.003	1.67	0.1	0.1	0.1	0.1	8.1	0.1	0.03	300	1.18
22-Jan-97	0.058	0.1	0.78	0.007	0.79	0.1	0.1	0.1	0.1	7.5	0.1	0.03	440	6.2
29-Jan-97	0.074	0.1	0.69	0.01	0.7	0.1	0.1	0.1	0.1	7.4	0.1	0.04	3	6.5
06-Feb-97	0.035	0.1	1.85	0.003	1.86	0.1	0.1	0.1	0.1	8.1	0.1	0.03	230	3.08
12-Feb-97	0.427	0.1	3.31	0.016	3.32	0.1	0.1	0.1	0.1	7.5	0.1	0.06	5000	15.9
26-Feb-97	0.088	0.1	0.82	0.019	0.84	0.1	0.1	0.1	0.1	7.1	0.1	0.04	46	6.2
05-Mar-97	0.048	0.1	1.1	0.012	1.11	0.1	0.1	0.1	0.1	7.6	0.1	0.03	680	4
12-Mar-97	0.03	0.1	1.12	0.007	1.13	0.1	0.1	0.1	0.1	8.1	0.1	0.03	210	3.94
19-Mar-97	0.053	0.1	4.17	0.011	4.18	0.1	0.1	0.1	0.1	7.6	0.1	0.03	830	10.1
26-Mar-97	0.06	0.1	0.83	0.003	0.84	0.1	0.1	0.1	0.1	7.2	0.1	0.03	500	1.93
02-Apr-97	0.051	0.1	1.06	0.004	1.07	0.1	0.1	0.1	0.1	7.9	0.1	0.03	1640	1.84
07-Apr-97	0.153	0.1	1.02	0.004	1.02	0.1	0.1	0.1	0.1	7.8	0.47	0.03	520	2.1
16-Apr-97	0.074	0.1	0.79	0.006	0.8	0.1	0.1	0.1	0.1	7.1	0.1	0.03	490	2.7
23-Apr-97	0.063	0.1	0.66	0.005	0.67	0.1	0.1	0.1	0.1	7.2	0.1	0.03	60	2.6
30-Apr-97	0.237	0.1	0.9	0.003	0.91	0.1	0.1	0.1	0.1	8.1	0.1	0.03	1220	3.8
07-May-97	0.041	0.1	1.47	0.003	1.47	0.1	0.1	0.1	0.1	8.1	0.1	0.03	2760	1.8
14-May-97	0.052	0.1	1.06	0.005	1.06	0.1	0.1	0.1	0.1	8.1	0.1	0.03	3800	2.4
21-May-97	0.055	0.1	1.05	0.003	1.05	0.1	0.1	0.1	0.1	8.3	0.1	0.03	250	1.45
28-May-97	0.062	0.1	0.68	0.008	0.68	0.1	0.1	0.1	0.1	7.1	0.1	0.03	230	1.54
04-Jun-97	0.061	0.1	0.66	0.008	0.67	0.1	0.1	0.1	0.1	6.6	0.1	0.03	50	1.97
11-Jun-97	0.071	0.1	0.66	0.009	0.66	0.1	0.1	0.1	0.1	7.3	0.1	0.03	4500	3.4
18-Jun-97	0.074	0.1	0.8	0.007	0.8	0.1	0.1	0.1	0.1	7.4	0.1	0.03	1880	2.6
25-Jun-97	0.056	0.1	0.65	0.005	0.66	0.1	0.1	0.1	0.1	7.5	0.1	0.03	160	2.1
02-Jul-97	0.103	0.1	0.93	0.003	0.93	0.1	0.1	0.1	0.1	8.1	0.1	0.03	1800	1.1
09-Jul-97	0.123	0.1	0.58	0.005	0.59	0.1	0.1	0.1	0.1	7.2	0.1	0.03	250	1.66
16-Jul-97	0.065	0.1	0.61	0.006	0.62	0.1	0.1	0.1	0.1	7.7	0.1	0.03	900	1.72
23-Jul-97	0.049	0.1	0.69	0.006	0.7	0.1	0.1	0.1	0.1	7.2	0.1	0.03	250	1.89
30-Jul-97	0.055	0.1	0.68	0.005	0.68	0.1	0.1	0.1	0.1	7.6	0.1	0.03	140	1.58

Sample site 7	Howgill Beck @ Howgill																	
Date	Parameter	Glostridium Peffringens	Coliforms - isolated but do not confirm	Colour (F/Barat)	Conductivity (20 C)	E. Coll	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	pH	Total Ammonia	Total Coliforms	Turbidity
23-Oct-96	Aluminium	30	1530	67.3	256	0	640	640	160	0.25	0.01	1.63	0.005	1.63	8.1	0.03	1530	2.14
30-Oct-96		50	210	69.7	244	0	90	90	50	0.289	0.008	1.86	0.005	1.86	8.2	0.03	210	1.76
06-Nov-96		410	2360	90.8	187	0	2080	2080	230	0.712	0.015	1.99	0.014	2.01	7.6	0.03	2360	10.3
13-Nov-96		160	960	62.4	300	0	150	150	30	0.257	0.015	1.83	0.004	1.83	8.1	0.03	960	1.88
20-Nov-96		180	4000	38	306	0	4020	4020	250	0.232	0.019	2.46	0.009	2.47	7.9	0.1	4000	4.26
27-Nov-96		90	350	53.3	228	0	110	110	30	0.312	0.02	2.27	0.005	2.28	8	0.03	350	2.56
04-Dec-96		50	840	84.5	195	0	240	240	40	0.267	0.015	1.75	0.003	1.76	7.8	0.03	840	3.11
11-Dec-96		60	270	31.4	274	0	330	330	40	0.09	0.009	2.26	0.003	2.26	8	0.03	270	1.23
18-Dec-96		400	210	32.1	288	0	230	230	70	0.134	0.008	2.01	0.008	2.01	8.1	0.06	270	1.42
03-Jan-97		30	400	29.2	270	0	280	280	60	0.015	0.002	2.06	0.003	2.06	8.1	0.03	400	1
08-Jan-97		0	1340	12.8	287	0	280	280	150	0.019	0.006	1.99	0.003	1.99	8.2	0.03	1340	0.79
15-Jan-97		30	60	44	231	0	30	30	10	0.14	0.005	1.72	0.005	1.73	8.1	0.03	60	1.52
22-Jan-97		0	1760	19.7	279	0	1760	1760	50	0.082	0.005	1.85	0.003	1.85	8.2	0.03	1760	2.86
29-Jan-97		0	36	30.9	280	0	14	14	0	0.079	0.004	1.73	0.003	1.73	8.2	0.03	36	1.5
06-Feb-97		80	580	55	222	0	170	170	120	0.225	0.006	1.68	0.004	1.68	8.2	0.03	580	2.52
12-Feb-97		5000	2640	142	152	0	1640	1640	130	1.18	0.189	3.33	0.017	3.34	7.4	0.14	2640	16.4
26-Feb-97		140	55	64.2	182	0	36	36	110	0.256	0.02	1.51	0.006	1.51	7.7	0.04	55	5.2
05-Mar-97		20	260	26.3	262	0	50	50	20	0.097	0.011	2.26	0.003	2.26	8.2	0.03	260	1.55
12-Mar-97		10	720	20.4	286	0	70	70	20	0.057	0.004	2.05	0.003	2.05	8.4	0.03	720	0.87
19-Mar-97		200	1460	56.7	250	0	180	180	180	0.206	0.006	3.12	0.003	3.12	8.3	0.03	1460	1.84
26-Mar-97		10	5000	62.6	248	0	680	680	270	0.201	0.006	1.49	0.005	1.5	8	0.03	5000	1.02
02-Apr-97		20	9000	20.9	280	0	780	780	250	0.08	0.005	1.78	0.004	1.78	8.5	0.03	9000	1.11
07-Apr-97		30	1000	16.6	289	0	720	720	130	0.051	0.003	1.74	0.003	1.75	8.3	0.03	1000	1.05
16-Apr-97		10	260	7.2	295	0	400	400	90	0.023	0.003	1.72	0.003	1.72	8.6	0.03	260	0.75
23-Apr-97		40	370	52.6	256	0	320	320	70	0.02	0.003	1.58	0.003	1.58	8.5	0.03	370	0.93
30-Apr-97		80	2080	61.8	234	0	1040	1040	220	0.224	0.017	1.16	0.006	1.19	8.3	0.06	2080	3.7
07-May-97		100	1800	61.8	209	0	640	640	230	0.337	0.009	1.26	0.004	1.27	8.1	0.03	1800	2.2
14-May-97		60	1440	51.9	280	0	960	960	100	0.008	0.001	1.14	0.005	1.14	7.9	0.03	1440	1.8
21-May-97		40	11000	24	292	0	1160	1160	170	0.159	0.031	1.53	0.006	1.53	8.3	0.03	11000	0.81
28-May-97		0	900	9	294	0	940	940	190	0.037	0.007	1.68	0.005	1.69	8.4	0.03	900	1.2
04-Jun-97		50	0	49.7	255	0	6000	0	6240	0.656	0.189	1.88	0.06	1.89	7.7	0.68	6000	32
11-Jun-97		40	2240	64	257	0	2120	2120	650	0.206	0.014	1.38	0.005	1.39	8.1	0.03	2240	1.41
18-Jun-97		80	3180	58.8	260	0	2100	2100	1140	0.204	0.013	1.26	0.005	1.27	8.1	0.03	3180	1.82
25-Jun-97		30	3400	57.3	253	0	2400	2400	510	0.214	0.009	1.37	0.005	1.37	8.1	0.03	3400	1.18
02-Jul-97		0	2800	29.5	285	0	1720	1720	620	0.116	0.01	1.32	0.004	1.32	8.1	0.03	2800	0.47
09-Jul-97		60	340	11.5	300	0	280	280	1800	0.057	0.007	1.31	0.004	1.31	8.2	0.03	340	0.31
16-Jul-97		130	4600	7.9	296	0	2420	2420	640	0.134	0.006	1.45	0.003	1.45	8.2	0.03	4600	1.05
23-Jul-97		140	2200	10	292	0	2200	2200	600	0.043	0.008	1.35	0.003	1.35	8.4	0.03	2200	0.89

Date	Hexachlorobenzene	Imazapyr	Ioxynil	Iprodione	Iron (total)	Isodrin	Isoproturon	Linuron	Malathion	Manganese (total)	MCPA	MCPB	MCPP	Methoxychlor	Monuron	Nitrate	Nitrite	Nitrogen - total oxidized	OP - DDT	Oxadixyl	Parathion
23-Oct-86					0.117					0.008						1.4	0.003	1.41			
30-Oct-86					0.154					0.011						1.52	0.003	1.52			
06-Nov-86				0.02	0.606				0.02	0.057						1.18	0.011	1.19		0.03	0.02
13-Nov-86					0.136					0.01						1.6	0.003	1.6			
20-Nov-86					0.295					0.051						1.45	0.005	1.45			
27-Nov-86					0.157					0.022						1.75	0.003	1.75			
04-Dec-86				0.02	0.276				0.02	0.059						1.08	0.004	1.09		0.03	0.02
11-Dec-86					0.068					0.011						1.94	0.003	1.94			
18-Dec-86					0.105					0.007						1.62	0.004	1.62			
03-Jan-87					0.118					0.002						1.93	0.003	1.93			
08-Jan-87					0.081					0.009						1.83	0.003	1.83			
15-Jan-87					0.124					0.004						1.37	0.003	1.37			
22-Jan-87					0.146					0.009						1.4	0.003	1.41			
28-Jan-87					0.102					0.01						1.15	0.003	1.15			
06-Feb-87					0.767					0.006						1.45	0.003	1.45			
12-Feb-87					0.458					0.098						3.47	0.005	3.48			
28-Feb-87					0.178					0.076						0.88	0.005	0.88			
05-Mar-87					0.298					0.023						1.13	0.003	1.13			
12-Mar-87					0.14					0.009						1.52	0.003	1.52			
19-Mar-87					0.063					0.011						3.54	0.004	3.55			
28-Mar-87					0.057					0.008						0.97	0.003	0.97			
07-Apr-87					0.179					0.005						1.14	0.003	1.15			
16-Apr-87					0.171					0.014						1.31	0.003	1.31			
23-Apr-87					0.11					0.012						1.16	0.004	1.16			
30-Apr-87	0.005	0.02	0.02	0.02	0.11	0.005	0.01	0.02	0.02	0.012	0.03	0.04	0.02	0.02	0.01	1.96	0.003	1.06	0.03	0.03	0.02
07-May-87					0.131					0.007						0.98	0.003	0.73	0.01		
14-May-87					0.175					0.009						0.98	0.003	0.98			
21-May-87					0.086					0.012						0.82	0.003	0.83			
28-May-87					0.165					0.008						1	0.003	1			
04-Jun-87	0.005	0.02	0.02	0.02	0.146	0.005	0.01	0.02	0.02	0.008	0.03	0.04	0.02	0.02	0.01	1.12	0.005	1.12	0.01	0.03	0.02
11-Jun-87					0.221					0.012						1.04	0.006	1.04			
18-Jun-87					0.153					0.085						0.76	0.006	0.76			
25-Jun-87					0.123					0.022						1.11	0.007	1.11			
02-Jul-87	0.005	0.02	0.02	0.02	0.123	0.005	0.01	0.02	0.02	0.013	0.03	0.04	0.02	0.02	0.01	0.92	0.005	0.92	0.01	0.03	0.02
09-Jul-87					0.236					0.013						0.88	0.004	0.88			
16-Jul-87					0.143					0.017						0.91	0.006	0.92			
23-Jul-87	0.005	0.02	0.02	0.02	0.196	0.005	0.01	0.02	0.02	0.016	0.03	0.04	0.02	0.02	0.01	0.97	0.006	0.98	0.01	0.03	0.02
30-Jul-87					0.166					0.014						0.87	0.006	0.87			

Sample site 9	Barden Beck @ Strid Wood																	
Date	Parameter	Clostridium Perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	E. Coli	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	pH	Total Ammonia	Total Coliforms	Turbidity
23-Oct-96	Aluminium	0.076	400	31	159	0	110	110	20	0.134	0.012	0.83	0.003	0.83	7.8	0.03	400	0.76
30-Oct-96		0.074	210	27.8	143	0	80	80	30	0.127	0.012	1	0.003	1	7.8	0.03	210	0.68
06-Nov-96		0.53	900	57.6	106	0	480	480	70	0.473	0.093	1.22	0.005	1.22	7.2	0.03	900	3.1
13-Nov-96		0.126	160	18.9	129	0	40	40	10	0.125	0.035	1.07	0.003	1.07	7.5	0.03	160	1.03
20-Nov-96		0.436	1160	64.4	104	0	1080	1080	60	0.409	0.077	0.77	0.004	0.77	7.2	0.03	1160	3.09
27-Nov-96		0.252	200	24.8	124	0	30	30	0	0.233	0.062	1.25	0.003	1.25	7.4	0.03	200	1.7
04-Dec-96		0.464	200	61.8	80	0	70	70	10	0.312	0.079	0.91	0.003	0.91	6.8	0.03	200	2.6
11-Dec-96		0.088	150	15.4	143	0	100	100	10	0.089	0.018	1.19	0.003	1.19	7.6	0.03	150	0.81
18-Dec-96		0.079	200	16.5	154	0	130	130	50	0.108	0.012	1.07	0.003	1.07	7.6	0.03	200	1.01
03-Jan-97		0.01	140	7.5	163	0	50	50	0	0.014	0.003	1.26	0.003	1.26	7.7	0.03	140	0.73
08-Jan-97		0.051	380	6.4	160	0	180	180	40	0.06	0.01	1.21	0.004	1.21	7.5	0.03	380	0.5
15-Jan-97		0.032	60	9.7	167	0	30	30	10	0.159	0.123	1.02	0.004	1.02	7.5	0.03	60	0.87
22-Jan-97		0.044	150	8	276	0	90	90	10	0.06	0.01	1.11	0.003	1.11	7.9	0.03	150	0.98
29-Jan-97		0.067	6	8.7	145	0	8	8	0	0.089	0.012	0.81	0.003	0.81	7.8	0.03	6	2.3
06-Feb-97		0.134	70	22.7	151	0	60	60	10	0.203	0.033	0.95	0.003	0.95	7.8	0.03	70	1.43
12-Feb-97		0.985	1360	89.3	111	0	760	760	110	1.75	0.286	3.48	0.006	3.48	7.1	0.03	1360	10.8
26-Feb-97		0.668	90	94.1	75	0	3	3	20	0.542	0.09	0.81	0.005	0.81	6.1	0.05	12	7.3
05-Mar-97		0.257	140	44.9	98	0	10	10	10	0.186	0.03	0.69	0.003	0.69	7.4	0.03	140	1.49
12-Mar-97		0.083	70	12.8	154	0	50	50	20	0.084	0.011	1.04	0.003	1.04	7.9	0.03	70	0.69
19-Mar-97		0.191	440	31.6	130	0	90	90	10	0.205	0.018	0.76	0.003	0.76	7.8	0.03	440	1.34
26-Mar-97		0.164	160	27.6	130	0	160	160	10	0.164	0.018	0.78	0.003	0.78	7.9	0.03	160	1.6
02-Apr-97		0.066	380	10.4	164	0	50	50	10	0.078	0.026	0.82	0.003	0.82	7.9	0.03	380	0.46
07-Apr-97		0.053	270	10.2	162	0	40	40	10	0.059	0.006	0.85	0.003	0.85	8.1	0.03	270	0.82
16-Apr-97		0.048	30	9.4	172	0	250	250	10	0.058	0.012	0.93	0.003	0.93	8	0.03	30	0.31
23-Apr-97		0.047	80	5.7	174	0	40	40	10	0.029	0.004	0.74	0.003	0.74	8.2	0.03	80	0.75
30-Apr-97		0.083	300	16.3	168	0	20	20	10	0.108	0.02	0.53	0.003	0.53	7.8	0.03	300	0.86
07-May-97		0.184	520	49.2	133	0	510	510	60	0.189	0.015	0.76	0.003	0.76	7.6	0.03	520	1.04
14-May-97		0.204	2400	46.1	123	0	150	150	70	0.317	0.024	0.56	0.003	0.56	7.5	0.03	2400	1.28
21-May-97		0.075	210	25.2	151	0	160	160	40	0.113	0.007	0.65	0.003	0.65	7.8	0.03	210	1.34
28-May-97		0.041	700	10.7	170	0	50	50	10	0.044	0.007	0.77	0.003	0.77	7.9	0.03	700	0.2
04-Jun-97		0.044	250	7.3	148	0	360	360	120	0.053	0.007	0.78	0.003	0.78	7.9	0.03	250	0.62
11-Jun-97		0.205	21000	37.1	128	0	13000	13000	3320	0.482	0.078	0.61	0.004	0.61	7.4	0.03	21000	3.8
18-Jun-97		0.027	120	19	172	0	110	110	40	0.059	0.012	0.89	0.003	0.89	7.9	0.03	120	0.33
25-Jun-97		0.029	1360	10.2	163	0	170	170	170	0.09	0.013	0.82	0.003	0.82	7.8	0.03	1360	0.56
02-Jul-97		0.103	1000	26.2	162	0	310	310	110	0.26	0.034	0.8	0.003	0.8	7.8	0.03	1000	0.67
09-Jul-97		0.081	40	24	166	0	410	410	50	0.209	0.044	0.79	0.003	0.79	7.8	0.03	40	0.42
16-Jul-97		0.052	740	14.3	169	0	300	300	60	0.134	0.014	0.69	0.003	0.69	8	0.03	740	0.41
23-Jul-97		0.021	600	7.3	173	0	130	130	250	0.064	0.01	0.83	0.003	0.83	7.9	0.03	600	0.57
30-Jul-97		0.03	220	11.8	169	0	160	160	60	0.115	0.011	0.75	0.003	0.75	8	0.03	220	0.57

Sample site 10	Haw Beck @ Bolton Bridge																		
Date	Parameter	Clostridium Peetrifingens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	E. Coll	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	Oil & Grease - Total	pH	Total Ammonia	Total Coliforms	Turbidity
23-Oct-96	Aluminium	0.04	70	1320	18.9	554	620	620	990	0.093	0.014	2.96	0.007	2.98	0.05	8.4	0.03	1320	1.61
30-Oct-96	0.395	1100	3500	24.6	390	390	1780	1780	990	0.544	0.06	2.61	0.013	2.63	0.06	8	0.03	3500	14.5
06-Nov-96	0.74	740	5000	39.7	452	452	3880	3880	1440	0.651	0.09	7.42	0.036	7.45	0.03	7.9	0.06	5000	11.3
13-Nov-96	0.102	350	2840	21.8	523	523	1640	1640	520	0.148	0.017	6.08	0.019	6.08	0.03	8.3	0.03	2840	3.41
20-Nov-96	0.623	920	5000	34.3	445	445	2320	2320	40	0.651	0.057	6.15	0.03	6.15	0.03	7.8	0.12	5000	18
27-Nov-96	0.124	400	4000	17.7	536	536	480	480	220	0.164	0.025	7.18	0.018	7.2	0.03	8.2	0.03	4000	3.16
04-Dec-96	0.289	300	4700	28.9	490	490	1240	1240	170	0.271	0.015	6.22	0.024	6.53	0.03	8.1	0.07	4700	7
18-Dec-96	0.189	120	880	11.2	588	588	280	280	30	0.06	0.024	4.86	0.049	6.25	0.03	8.1	0.03	880	1.49
03-Jan-97	0.01	120	800	7.5	713	713	470	470	390	0.196	0.002	6.22	0.023	5.01	0.03	8.1	0.06	800	6.2
08-Jan-97	0.033	650	1140	9.5	513	513	390	390	390	0.012	0.002	5.67	0.027	5.7	0.03	8.2	0.06	800	2.02
15-Jan-97	0.034	360	6000	9.2	547	547	410	410	210	0.083	0.014	5.07	0.02	5.09	0.03	8.3	0.03	1140	1.18
22-Jan-97	0.048	150	760	9.7	1530	1530	230	230	120	0.098	0.008	4.97	0.02	4.99	0.03	8.3	0.03	6000	0.94
28-Jan-97	0.025	30	76	10.2	589	589	640	640	200	0.081	0.013	13.8	0.027	13.8	0.04	8.3	0.03	760	2.13
06-Feb-97	0.077	2200	510	21	512	512	23	23	0	0.116	0.006	4.11	0.01	4.12	0.04	8.5	0.03	78	1.94
12-Feb-97	3.99	10000	7000	57.4	357	357	470	470	270	0.135	0.011	5.02	0.025	5.04	0.03	8.6	0.15	510	3.3
26-Feb-97	1.13	5000	640	45.5	357	357	180	180	710	0.396	0.05	4.9	0.074	4.97	0.03	7.6	0.28	7000	82
05-Mar-97	0.067	140	1840	17.1	522	522	300	300	50	0.088	0.011	6.27	0.019	6.29	0.03	7.8	0.27	640	640
12-Mar-97	0.145	30	920	10.2	564	564	290	290	70	0.068	0.009	5.77	0.014	5.78	0.03	8.4	0.04	1840	1.98
26-Mar-97	0.065	260	4600	33.3	469	469	230	230	70	0.204	0.011	3.88	0.026	3.91	0.03	8.5	0.03	920	1.1
19-Apr-97	0.022	470	8000	12.7	483	483	70	70	10	0.124	0.004	4.8	0.016	4.82	0.03	8.9	0.07	4600	4.3
07-Apr-97	0.027	890	1800	10.9	521	521	280	280	10	0.072	0.007	4.8	0.012	4.82	0.03	8.6	0.03	540	1.91
16-Apr-97	0.211	820	260	30.9	165	165	310	310	10	0.08	0.008	4.29	0.015	4.31	0.03	8.6	0.03	8000	1.17
23-Apr-97	0.024	1490	200	11	465	465	27	27	100	0.247	0.027	1.42	0.004	1.43	0.03	8.9	0.03	1800	1.61
30-Apr-97	0.049	210	890	17.1	462	462	190	190	40	0.056	0.006	3.37	0.006	3.37	0.03	8.9	0.03	280	2.2
07-May-97	0.115	140	1400	22.2	498	498	90	90	40	0.125	0.013	2.24	0.009	2.25	0.03	8.9	0.03	200	1.89
14-May-97	0.195	330	2000	25.4	448	448	1080	1080	230	0.16	0.013	3.47	0.011	3.48	0.03	8.4	0.03	890	1.34
21-May-97	0.05	290	700	17.9	518	518	480	480	190	0.253	0.014	3.11	0.009	3.11	0.03	8.5	0.03	1400	2.1
28-May-97	0.054	210	310	14	524	524	780	780	190	0.11	0.009	3.39	0.012	3.4	0.03	8.5	0.03	2000	3.2
04-Jun-97	0.02	300	1300	12.4	566	566	310	310	170	0.11	0.002	3.58	0.018	3.6	0.03	8.7	0.03	700	2.5
11-Jun-97	1.86	3000	0	51.1	364	364	810	810	160	0.056	0.008	3.79	0.018	3.81	0.03	8.7	0.03	310	1.84
18-Jun-97	0.017	80	5000	15.3	547	547	60000	60000	1.83	0.097	0.194	3.17	0.156	3.28	0.03	8.7	0.03	1300	1.27
25-Jun-97	0.022	580	3200	13.6	546	546	1360	1360	130	0.089	0.008	3.46	0.024	3.46	0.03	8.5	0.48	60000	4.1
02-Jul-97	0.027	320	4200	20.6	519	519	1540	1540	250	0.067	0.008	1.47	0.022	1.49	0.04	8.2	0.03	5000	1.06
09-Jul-97	0.036	50	4320	13.4	565	565	2600	2600	120	0.118	0.011	2.55	0.014	2.57	0.03	8.4	0.03	4200	1.07
16-Jul-97	0.033	110	3200	14.2	544	544	1440	1440	210	0.098	0.011	4.56	0.007	4.57	0.03	8.3	0.03	4320	0.57
23-Jul-97	0.028	200	3200	15.1	2180	2180	880	880	20	0.089	0.007	2.86	0.008	2.99	0.04	8.5	0.03	3200	0.64
30-Jul-97	0.024	10	6240	16.9	485	485	110	110	470	0.056	0.008	3.19	0.01	3.2	0.04	8.3	0.03	3200	1.36
							1800	1800	273	0.08	0.007	2.72	0.011	2.73	0.03	8.6	0.04	6240	1.51

Sample site 11	River Wharfe @ Bolton Bridge																	
Parameter	Coliforms - isolated but do not confirm	Coliforms	Faecal Coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	Oil & Grease - Total	pH	Total Ammonia	Total Coliforms	Turbidity				
Date	Aluminium	Chloride	Conductivity (20 C)	Colour (Filtered)	E. Coli	Faecal Coliforms	Faecal Coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidised	Oil & Grease - Total	pH	Total Ammonia	Total Coliforms	Turbidity
23-Oct-96	0.054	20	381	381	270	390	390	70	0.117	0.005	1.57	0.003	1.58	0.03	8.4	0.03	800	1.23
30-Oct-96	0.057	30	27	27	0	400	400	870	0.158	0.006	1.08	0.004	1.68	0.003	8.3	0.03	1400	2.33
06-Nov-96	0.81	270	164	164	0	2150	2160	250	0.054	0.009	1.23	0.01	1.24	0.003	7.8	0.03	2500	10.9
13-Nov-96	0.1	60	347	347	0	350	350	300	0.143	0.01	1.88	0.003	1.66	0.003	8.2	0.03	400	2.12
20-Nov-96	0.217	320	286	286	0	1040	1040	1040	0.227	0.023	2.29	0.008	2.29	0.003	8	0.04	8000	4.1
27-Nov-96	0.118	100	29	29	0	130	130	150	0.136	0.011	2.12	0.003	2.12	0.003	8.2	0.03	310	1.54
04-Dec-96	0.157	90	36.2	36.2	0	430	430	130	0.153	0.01	1.41	0.004	1.42	0.003	8	0.03	780	3.82
11-Dec-96	0.04	30	19.8	19.8	0	370	370	140	0.072	0.007	2.68	0.003	2.69	0.003	8.1	0.03	1040	1.15
18-Dec-96	0.058	70	25.7	25.7	0	150	150	180	0.104	0.004	1.94	0.006	1.95	0.003	8.1	0.03	890	0.92
03-Jan-97	0.01	70	209	209	0	290	290	130	0.103	0.002	2.19	0.004	2.2	0.003	8.3	0.03	440	0.76
08-Jan-97	0.082	0	18.4	18.4	0	230	230	70	0.103	0.005	2.21	0.003	2.21	0.003	8.3	0.03	840	0.76
15-Jan-97	0.093	40	20.2	20.2	0	100	100	50	0.084	0.003	1.55	0.004	1.55	0.003	8.2	0.03	200	1.82
22-Jan-97	0.091	30	247	247	0	8	8	50	0.188	0.007	1.75	0.003	1.75	0.003	8.2	0.03	350	1.76
28-Jan-97	0.078	0	32	32	0	8	8	2	0.183	0.006	1.48	0.005	1.48	0.003	8.3	0.03	11	1.34
05-Feb-97	0.093	80	257	257	0	230	230	80	0.107	0.008	1.91	0.003	1.91	0.003	8.3	0.03	230	2.87
12-Feb-97	0.111	400	197	197	0	520	520	190	0.457	0.04	3.45	0.005	3.45	0.003	7.8	0.03	1120	16.9
26-Feb-97	0.204	200	41.7	41.7	0	73	73	180	0.215	0.019	1.38	0.004	1.39	0.003	8	0.03	200	5.1
05-Mar-97	0.078	20	22.4	22.4	0	60	60	60	0.093	0.007	2.36	0.003	2.28	0.003	8.3	0.03	300	1.28
12-Mar-97	0.042	10	13.9	13.9	0	210	210	90	0.086	0.003	2.23	0.003	2.24	0.003	8.4	0.03	310	1.04
19-Mar-97	0.208	50	49.6	49.6	0	210	210	170	0.279	0.007	3.61	0.004	3.52	0.003	8.2	0.03	860	3.3
26-Mar-97	0.057	70	32.2	32.2	0	120	120	10	0.117	0.001	1.18	0.003	1.19	0.003	8.7	0.03	190	1.51
02-Apr-97	0.035	10	18.6	18.6	0	210	210	30	0.055	0.003	1.49	0.004	1.49	0.003	8.6	0.03	530	1.05
07-Apr-97	0.027	30	13.6	13.6	0	80	80	10	0.044	0.003	1.82	0.004	1.83	0.003	8.7	0.03	860	1.28
14-Apr-97	0.1	50	50.1	50.1	0	80	80	10	0.22	0.011	1.43	0.005	1.43	0.003	8.6	0.03	21	1.47
23-Apr-97	0.104	30	47.5	47.5	0	90	90	10	0.207	0.01	1.37	0.004	1.38	0.003	8.4	0.03	260	1.03
30-Apr-97	0.079	70	36.4	36.4	0	90	90	50	0.135	0.006	0.77	0.003	0.77	0.003	8.6	0.03	490	1.44
07-May-97	0.109	40	25.8	25.8	0	860	860	140	0.119	0.007	1.13	0.003	1.13	0.003	8.2	0.03	1440	1.95
14-May-97	0.087	50	35.3	35.3	0	290	290	210	0.113	0.005	1.2	0.003	1.21	0.003	8.3	0.03	3500	1.3
21-May-97	0.031	70	19.6	19.6	0	320	320	70	0.095	0.005	1.53	0.004	1.54	0.003	8.5	0.03	410	1.36
28-May-97	0.077	80	38.3	38.3	0	190	190	90	0.175	0.008	1.39	0.007	1.39	0.003	8.5	0.03	260	0.83
04-Jun-97	0.065	10	48.9	48.9	0	130	130	110	0.202	0.01	1.35	0.01	1.36	0.003	8.4	0.03	160	1.45
11-Jun-97	0.142	80	46.7	46.7	0	3900	3900	2000	0.012	0.019	1.38	0.012	1.39	0.003	7.9	0.06	10000	2.6
18-Jun-97	0.097	30	44.5	44.5	0	470	470	130	0.241	0.021	1.22	0.008	1.23	0.003	8.3	0.03	860	1.21
25-Jun-97	0.072	40	23.8	23.8	0	800	800	130	0.18	0.018	0.89	0.006	0.9	0.003	8.2	0.03	1880	1.63
02-Jul-97	0.065	20	32	32	0	1800	1800	90	0.123	0.011	1.07	0.006	1.08	0.003	8.3	0.03	1600	1.1
09-Jul-97	0.098	20	30	30	0	620	620	80	0.14	0.019	1.9	0.007	1.91	0.003	8.1	0.03	1130	1.02
16-Jul-97	0.064	70	27.4	27.4	0	1040	1040	110	0.148	0.015	1.07	0.007	1.07	0.003	8.4	0.03	2200	0.48
23-Jul-97	0.08	50	24.4	24.4	0	35	35	90	0.2	0.015	1.07	0.006	1.08	0.003	8.1	0.03	920	1.04
30-Jul-97	0.056	10	42.8	42.8	0	650	650	90	0.159	0.013	0.94	0.006	0.95	0.003	8.1	0.03	1040	1.04

Sample site 12		Van Beck & Beemster																		
Average of Valve	Parameter	Gloetidium Perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 °C)	Cryptosporidium	E. Coli	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Iron (total)	Manganese (total)	Nitrate	Nitrite	Nitrogen - total oxidized	Oil & Grease - Total	pH	Total Ammonia	Total Coliforms	Turbidity
23-Oct-98	Aluminium	0.175	10	57.4	214	0	0	260	260	50	0.469	0.021	1.03	0.006	1.04	0.03	7.8	0.03	260	3.72
30-Oct-98	Aluminium	0.189	190	45.5	201	0	0	500	500	640	0.476	0.022	1.5	0.005	1.5	0.03	7.9	0.03	600	2.9
06-Nov-98	Aluminium	0.524	370	2940	53.8	0.4	0	1100	1100	650	0.701	0.073	2.89	0.012	2.9	0.03	7.3	0.03	2540	4.6
13-Nov-98	Aluminium	0.273	130	250	185	0	0	180	180	300	0.403	0.027	2.82	0.004	2.82	0.03	7.7	0.03	340	3.04
20-Nov-98	Aluminium	0.415	110	8000	38.1	0	0	1000	1000	350	0.48	0.047	3.76	0.014	3.76	0.03	7.5	0.1	8000	7.2
27-Nov-98	Aluminium	0.308	110	180	43.2	0	0	140	140	80	0.387	0.037	3.29	0.007	3.3	0.03	7.6	0.03	180	4.7
04-Dec-98	Aluminium	0.37	50	70.4	173	0.2	0	470	470	160	0.364	0.038	2.9	0.007	2.9	0.03	7.8	0.04	750	3.68
11-Dec-98	Aluminium	0.119	10	25	209	0	0	18	18	20	0.218	0.02	2.72	0.007	2.72	0.03	7.8	0.04	150	1.97
18-Dec-98	Aluminium	0.213	140	35	254	0	0	260	260	130	0.368	0.021	1.96	0.021	1.96	0.03	7.8	0.05	35	1.97
03-Jan-97	Aluminium	0.01	20	217	207	0	0	200	200	170	0.11	0.002	2.33	0.006	2.33	0.03	7.8	0.12	1040	4.0
06-Jan-97	Aluminium	0.1	70	250	247	0.2	0	170	170	10	0.165	0.009	2.24	0.006	2.24	0.03	7.8	0.05	280	2.28
15-Jan-97	Aluminium	0.166	30	100	176	0	0	50	50	10	0.259	0.012	1.78	0.005	1.77	0.03	7.8	0.1	290	1.4
22-Jan-97	Aluminium	0.113	20	216	348	0	0	180	180	10	0.185	0.008	1.8	0.004	1.81	0.03	7.8	0.03	290	3.34
28-Jan-97	Aluminium	0.08	3	18	220	0	0	0	0	0	0.163	0.005	1.51	0.004	1.52	0.03	7.7	0.03	8	1.78
04-Feb-97	Aluminium	0.161	320	330	205	0.2	0	80	80	0	0.331	0.01	1.56	0.008	1.59	0.03	7.8	0.06	330	2.73
12-Feb-97	Aluminium	1.66	2000	500	483	0	0	2080	2080	750	2.18	0.217	3.28	0.026	3.31	0.03	7.2	0.2	5000	31
26-Feb-97	Aluminium	0.522	280	270	150	0	0	44	44	250	0.488	0.052	2.06	0.007	2.07	0.03	7.5	0.05	250	6.7
05-Mar-97	Aluminium	0.163	100	150	200	0.2	0	80	80	10	0.199	0.011	2.74	0.003	2.74	0.03	7.9	0.03	150	1.71
12-Mar-97	Aluminium	0.103	40	187	212	0	0	20	20	20	0.139	0.006	2.06	0.003	2.07	0.03	8.1	0.03	170	1.63
19-Mar-97	Aluminium	0.285	60	580	169	0	0	190	190	190	0.439	0.015	3.11	0.004	3.11	0.03	8.1	0.03	560	2.6
26-Mar-97	Aluminium	0.198	90	270	42.3	0	0	20	20	30	0.349	0.019	2.09	0.004	2.09	0.03	7.8	0.03	220	1.24
02-Apr-97	Aluminium	0.293	70	17.4	254	0.2	0	50	50	50	0.13	0.009	1.72	0.003	1.72	0.03	8.2	0.03	770	1.05
07-Apr-97	Aluminium	0.063	50	16	228	0	0	100	100	100	0.12	0.007	1.39	0.003	1.39	0.03	8.1	0.03	940	1.84
16-Apr-97	Aluminium	0.065	90	16.9	185	0	0	180	180	10	0.069	0.006	1.26	0.003	1.26	0.03	8.8	0.03	1100	1.18
21-Apr-97	Aluminium	0.049	50	234	244	0	0	230	230	10	0.06	0.006	0.94	0.003	0.94	0.03	8.8	0.03	350	1.39
30-Apr-97	Aluminium	0.243	40	560	197	0.4	0	110	110	70	0.374	0.018	0.54	0.003	0.55	0.03	8.5	0.03	560	2
07-May-97	Aluminium	0.238	60	527	198	0	0	390	390	80	0.35	0.015	1.64	0.004	1.64	0.03	7.9	0.03	470	2.2
14-May-97	Aluminium	0.25	40	70.8	175	0	0	70	70	70	0.448	0.011	1.7	0.006	1.72	0.03	7.8	0.03	1320	2.7
21-May-97	Aluminium	0.159	45	81	209	0.2	0	1300	1300	30	0.391	0.013	1.26	0.005	1.27	0.03	8	0.03	1400	2.8
28-May-97	Aluminium	0.097	90	184	249	0	0	160	160	160	0.58	0.012	1.4	0.006	1.4	0.03	8.2	0.03	400	0.78
04-Jun-97	Aluminium	0.052	320	11.9	258	0	0	800	800	40	0.095	0.02	1.26	0.007	1.26	0.03	8.1	0.03	800	0.83
11-Jun-97	Aluminium	1.05	560	57.3	205	0	0	20000	20000	5600	3.19	0.412	1.26	0.042	1.26	0.03	7.6	0.23	36000	17.3
18-Jun-97	Aluminium	0.111	70	1000	41	0.2	0	1120	1120	200	0.295	0.029	0.99	0.005	0.99	0.03	8	0.03	1600	1.2
25-Jun-97	Aluminium	0.072	78	694	190	0	0	1800	1800	620	0.178	0.015	0.68	0.008	0.68	0.03	7.9	0.03	2450	3.8
02-Jul-97	Aluminium	0.246	20	166	235	0	0	1600	1600	80	0.545	0.016	0.87	0.005	0.87	0.03	7.8	0.03	2500	19.2
09-Jul-97	Aluminium	0.097	50	70	226	0	0	450	450	140	0.25	0.016	0.74	0.003	0.74	0.03	8	0.03	720	0.68
16-Jul-97	Aluminium	0.115	98	301	233	0	0	3600	3600	760	0.304	0.014	0.94	0.004	0.94	0.03	8.1	0.03	4000	1.24
23-Jul-97	Aluminium	0.077	40	146	260	0.2	0	70	70	70	0.15	0.015	0.65	0.003	0.65	0.03	8.1	0.03	1480	0.79
30-Jul-97	Aluminium	0.058	30	31	258	0	0	830	830	40	0.288	0.014	0.73	0.007	0.73	0.03	8	0.03	980	0.81

Sample site 13	River Wharfe @ Lohwood Intake																		
	Parameter	2,4 -	2,4,5 -	2,4,6 -	2,4-dichlorophenol	2,6-dichlorophenol	2-chlorophenol	4-chlorophenol	Aldrin	Aluminium	Atrazine	Azinphos-methyl	Bentazone	Biphenox	BOD (total)	Bromosynil	Carbendazim	Carbamide	Carbophenithion
		DB	T	TCP															
29-Oct-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.058	0.083	0.02	0.02	0.02	1.33	0.02	0.02	0.03	0.02	0.02
30-Oct-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.643	0.02	0.02	0.02	2.46	0.02	0.02	0.03	0.02	0.02
05-Nov-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.003	0.097	0.02	0.02	0.02	1.43	0.02	0.02	0.03	0.02	0.02
13-Nov-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.241	0.241	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
20-Nov-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.008	0.078	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
04-Dec-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.162	0.162	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
11-Dec-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.038	0.038	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
18-Dec-96	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.056	0.056	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
03-Jan-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
08-Jan-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.061	0.061	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
16-Jan-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.072	0.072	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
22-Jan-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.068	0.068	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
29-Jan-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.065	0.065	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
05-Feb-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.081	0.081	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
06-Feb-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.049	0.049	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
12-Feb-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.534	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
26-Feb-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.237	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
05-Mar-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.076	0.076	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
12-Mar-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
19-Mar-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.211	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
26-Mar-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.071	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
02-Apr-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.044	0.044	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
07-Apr-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.065	0.028	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
15-Apr-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.1	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
23-Apr-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.103	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
30-Apr-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.116	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
07-May-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.109	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
14-May-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.063	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
21-May-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.032	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
28-May-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.073	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
04-Jun-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.064	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
11-Jun-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.281	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
18-Jun-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.092	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
25-Jun-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.202	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
02-Jul-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.056	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
09-Jul-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.06	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
16-Jul-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.068	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
23-Jul-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.088	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
30-Jul-97	0.02	0.04	0.02	0.1	0.1	0.1	0.1	0.1	0.005	0.051	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02

Sample site 13	Chlordane	Chlorobiphenyls	Chlorobenzene	Chloromalonil	Chlorotoluron	Chloroprotham	Chlorpyrifos	Dioppyrid	Clostridium perfringens	Coliforms - isolated but do not confirm	Colour (Filtered)	Conductivity (20 C)	Cryptosporidium	Cyanazine	DDD (ppm DOE OP)
23-Oct-96	0.005	0.03		0.01	0.02	0.04	0.03	0.02	40	1540	42.4	278			
30-Oct-96									100	1920	36.6	250		0.03	0.01
06-Nov-96	0.005	0.03	0	0.01	0.02	0.04	0.03	0.02	350	2840	62.6	167	0.2	0.03	
13-Nov-96									180	6000	380	249			
20-Nov-96	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	70	900	28.6	295		0.03	
27-Nov-96									40	50	36.8	51.5	0.2	0.03	
04-Dec-96	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	120	700	28.7	268			
11-Dec-96									0	390	14.3	306		0.03	0.01
18-Dec-96	0.005	0.03		0.01	0.02	0.04	0.03	0.02	80	970	22	205			
06-Jan-97									130	120	30.8	213	0.2	0.03	
15-Jan-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	40	690	33.1	255			
22-Jan-97									3	18	33.7	237		0.03	
29-Jan-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	190	180	27.7	239			
06-Feb-97									360	5000	54.5	167	0.2	0.03	
12-Feb-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	120	20000	39.2	201		0.03	
26-Feb-97									20	340	22.6	277			
05-Mar-97									40	300	14.5	298		0.03	
12-Mar-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	70	1000	51.9	188			
19-Mar-97									70	320	34	238		0.03	
26-Mar-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	80	530	17.3	260			
02-Apr-97									40	780	14	290	0.2	0.03	
07-Apr-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	180	420	50.8	219			
16-Apr-97									40	11	50	223		0.03	
23-Apr-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	50	260	38.5	217			
30-Apr-97									10	1200	35.8	254	0.2	0.03	
07-May-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	80	1200	39	262			
14-May-97									60	330	22	306		0.03	
21-May-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	20	180	39.7	250			
28-May-97									30	180	43	221	0.2	0.03	
04-Jun-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	400	24000	44.8	232			
11-Jun-97									60	690	50	217		0.03	
18-Jun-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	50	2860	51.8	230			
25-Jun-97									30	2000	47.4	254	0.2	0	
02-Jul-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	70	1200	40.2	255			
09-Jul-97									20	2500	27.7	214		0.03	
16-Jul-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	60	530	42.9	244			
23-Jul-97									60	940	41.5	249	0.2	0.03	
30-Jul-97	0.005	0.03	0.02	0.01	0.02	0.04	0.03	0.02	60	940	41.5	249			

Date	Desmetryne	Diazinon	Dicamba	Dichlobenil	Dichlorprop	Dichlorvos	Dieldrin	Dimethoate	Diuron	E. Coli	Endosulphan Alpha	Endosulphan Beta	Endrin	EPTC	Faecal Coliforms	Faecal coliforms (presumptive)	Faecal Streptococci	Fenitrothion	Fenoprop [2,4,5-TP]
23-Oct-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	490	520	60	0.02	0.02
30-Oct-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	520	530	80	0.02	0.02
06-Nov-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	2120	330	330	0.02	0.02
13-Nov-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	230	280	280	0.02	0.02
20-Nov-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	1000	410	410	0.02	0.02
27-Nov-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	140	140	80	0.02	0.02
04-Dec-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	420	420	110	0.02	0.02
11-Dec-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	30	30	80	0.02	0.02
18-Dec-96	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	110	150	150	0.02	0.02
03-Jan-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	360	60	60	0.02	0.02
08-Jan-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	250	90	60	0.02	0.02
15-Jan-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	90	40	40	0.02	0.02
22-Jan-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	6	6	60	0.02	0.02
29-Jan-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	7	6	6	0.02	0.02
06-Feb-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	130	320	320	0.02	0.02
12-Feb-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	1110	1110	190	0.02	0.02
26-Feb-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	640	250	250	0.02	0.02
05-Mar-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	60	80	50	0.02	0.02
12-Mar-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	150	150	40	0.02	0.02
19-Mar-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	290	280	170	0.02	0.02
26-Mar-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	80	60	10	0.02	0.02
02-Apr-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	80	80	10	0.02	0.02
07-Apr-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	90	90	10	0.02	0.02
16-Apr-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	130	130	10	0.02	0.02
23-Apr-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	4	4	20	0.02	0.02
30-Apr-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	100	100	30	0.02	0.02
07-May-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	1320	170	170	0.02	0.02
14-May-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	430	430	170	0.02	0.02
21-May-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	220	220	30	0.02	0.02
28-May-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	110	110	10	0.02	0.02
04-Jun-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	200	200	50	0.02	0.02
11-Jun-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	10000	2600	2600	0.02	0.02
18-Jun-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	410	410	70	0.02	0.02
25-Jun-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	1260	80	80	0.02	0.02
02-Jul-97	0	0.02	0.02	0.04	0.02	0	0.003	0	0.02	0	0.01	0.01	0.02	0.03	610	610	40	0	0.02
09-Jul-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	810	110	110	0.02	0.02
16-Jul-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	630	630	60	0.02	0.02
23-Jul-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	420	420	60	0.02	0.02
30-Jul-97	0.02	0.02	0.02	0.04	0.02	0.02	0.003	0.02	0.02	0	0.01	0.01	0.02	0.03	610	610	80	0.02	0.02

Date	Fenpropolilin	Fenpropylmerph	Fluazifop butyl	Fluroxypr	Flutriafol	Hexachloro f.3 butadiene	HCH - Alpha	HCH - Beta	HCH - Delta	HCH - Gamma (Lindane)	Hepachlor	Hepachlor Epoxida	Hexachloroberzene	Imazapyr	Isoxnil	Iprodione	Iron (total)	Isodin	Isoproturon
23-Oct-96	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005	0.004	0.005	0.02	0.02	0.02	0.15	0.005	0.01
30-Oct-96																	0.683		
06-Nov-96	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.14	0.005	0.01
13-Nov-96																	0.265		
20-Nov-96	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.068	0.005	0.01
27-Nov-96																	0.182		
04-Dec-96	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.064	0.005	0.01
11-Dec-96																	0.1		
18-Dec-96	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005	0.004	0.005	0.02	0.02	0.02	0.112	0.005	0.01
03-Jan-97																	0.091		
08-Jan-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.16	0.005	0.01
15-Jan-97																	0.164		
22-Jan-97	0.02	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.104	0.005	0.01
29-Jan-97																	0.585		
05-Feb-97	0	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.246	0.005	0.01
12-Feb-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.090	0.005	0.01
28-Feb-97																	0.282		
05-Mar-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.131	0.005	0.01
12-Mar-97																	0.063		
19-Mar-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.05	0.005	0.01
26-Mar-97																	0.211		
02-Apr-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.205	0.005	0.01
07-Apr-97																	0.228		
16-Apr-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.11	0.005	0.01
23-Apr-97																	0.087		
30-Apr-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.087	0.005	0.01
07-May-97																	0.172		
14-May-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.198	0.005	0.01
21-May-97																	0.418		
28-May-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.236	0.005	0.01
04-Jun-97																	0.568		
11-Jun-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.215	0.005	0.01
18-Jun-97																	0.138		
25-Jun-97	0.03	0	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.228	0.005	0.01
02-Jul-97																	0.151		
09-Jul-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.151	0.005	0.01
16-Jul-97																	0.151		
23-Jul-97	0.03	0.02	0.02	0.02	0.03	0.01	0.005	0.005	0.005	0.005	0.005		0.005	0.02	0.02	0.02	0.151	0.005	0.01
30-Jul-97																	0.151		

Sample site 13

Date	Linuron	Malathion	Manganese (total)	MCPA	MCPB	MCPP	M-cresol	Methoxychlor	Monuron	Nitrate	Nitrite	Nitrogen - total oxidised	O-cresol	Oil & Grease - Total	DP - DDT	Oxadifop	Parathion	P-cresol	Pendimethalin	Pentachlorophenol
23-Oct-96	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	1.69	0.005	1.5	0.1	0.03	0.01	0.03	0.02	0.1	0.1	0.1
30-Oct-96	0.02	0.02	0.007	0.03	0.04	0.02	0.1	0.01	0.02	1.81	0.003	1.82	0.1	0.03	0.01	0.03	0.02	0.1	0.1	0.1
06-Nov-96	0.02	0.02	0.051	0.03	0.04	0.02	0.1	0.01	0.02	1.91	0.01	1.92	0.1	0.03	0.01	0.03	0.02	0.1	0.1	0.1
13-Nov-96	0.02	0.02	0.008	0.03	0.04	0.02	0.1	0.01	0.02	1.71	0.003	1.71	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
20-Nov-96	0.02	0.02	0.028	0.03	0.04	0.02	0.1	0.01	0.02	2.62	0.009	2.63	0.1	0.03	0.01	0.03	0.02	0.16	0.03	0.1
27-Nov-96	0.02	0.02	0.008	0.03	0.04	0.02	0.1	0.01	0.02	2.21	0.003	2.21	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
04-Dec-96	0.02	0.02	0.01	0.03	0.04	0.02	0.1	0.01	0.02	1.51	0.004	1.51	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
11-Dec-96	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	2.71	0.004	2.71	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
18-Dec-96	0.02	0.02	0.003	0.03	0.04	0.02	0.1	0.01	0.02	1.9	0.006	1.91	0.1	0.04	0.01	0.03	0.02	0.1	0.03	0.1
03-Jan-97	0.02	0.02	0.002	0.03	0.04	0.02	0.1	0.01	0.02	2.28	0.005	2.28	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
08-Jan-97	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	2.23	0.004	2.23	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
15-Jan-97	0.02	0.02	0.003	0.03	0.04	0.02	0.1	0.01	0.02	1.54	0.004	1.54	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
22-Jan-97	0.02	0.02	0.007	0.03	0.04	0.02	0.1	0.01	0.02	1.74	0.003	1.74	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
29-Jan-97	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	1.66	0.006	1.66	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
06-Feb-97	0.02	0.02	0.004	0.03	0.04	0.02	0.1	0.01	0.02	1.81	0.003	1.81	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
12-Feb-97	0.02	0.02	0.048	0.03	0.04	0.02	0.1	0.01	0.02	3.42	0.007	3.43	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
26-Feb-97	0.02	0.02	0.023	0.03	0.04	0.02	0.1	0.01	0.02	1.5	0.005	1.51	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
05-Mar-97	0.02	0.02	0.007	0.03	0.04	0.02	0.1	0.01	0.02	2.32	0.003	2.33	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
12-Mar-97	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	2.25	0.003	2.25	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
19-Mar-97	0.02	0.02	0.007	0.03	0.04	0.02	0.1	0.01	0.02	3.5	0.004	3.5	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
26-Mar-97	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	1.28	0.003	1.28	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
02-Apr-97	0.02	0.02	0.003	0.03	0.04	0.02	0.1	0.01	0.02	1.53	0.004	1.53	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
07-Apr-97	0.02	0.02	0.004	0.03	0.04	0.02	0.1	0.01	0.02	1.6	0.004	1.61	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
16-Apr-97	0.02	0.02	0.011	0.03	0.04	0.02	0.1	0.01	0.02	1.98	0.005	1.98	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
23-Apr-97	0.02	0.02	0.009	0.03	0.04	0.02	0.1	0.01	0.02	1.34	0.004	1.35	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
30-Apr-97	0.02	0.02	0.022	0.03	0.04	0.02	0.1	0.01	0.02	0.76	0.003	0.76	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
07-May-97	0.02	0.02	0.006	0.03	0.04	0.02	0.1	0.01	0.02	1.1	0.003	1.12	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
14-May-97	0.02	0.02	0.006	0.03	0.04	0.02	0.1	0.01	0.02	1.2	0.003	1.2	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
21-May-97	0.02	0.02	0.005	0.03	0.04	0.02	0.1	0.01	0.02	1.37	0.004	1.37	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
28-May-97	0.02	0.02	0.004	0.03	0.04	0.02	0.1	0.01	0.02	1.32	0.007	1.33	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
04-Jun-97	0.02	0.02	0.041	0.03	0.04	0.02	0.1	0.01	0.02	1.31	0.01	1.32	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
11-Jun-97	0.02	0.02	0.044	0.03	0.04	0.02	0.1	0.01	0.02	1.5	0.02	1.52	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
18-Jun-97	0.02	0.02	0.018	0.03	0.04	0.02	0.1	0.01	0.02	1.11	0.006	1.12	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
25-Jun-97	0.02	0.02	0.024	0.03	0.04	0.02	0.1	0.01	0.02	0.99	0.006	0.99	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
02-Jul-97	0.02	0.02	0.060	0.03	0.04	0.02	0.1	0.01	0.02	0.98	0.006	0.98	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
09-Jul-97	0.02	0.02	0.018	0.03	0.04	0.02	0.1	0.01	0.02	1.06	0.007	1.06	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
16-Jul-97	0.02	0.02	0.017	0.03	0.04	0.02	0.1	0.01	0.02	1.03	0.007	1.04	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1
23-Jul-97	0.02	0.02	0.015	0.03	0.04	0.02	0.1	0.01	0.02	1.07	0.008	1.07	0.1	0.05	0.01	0.03	0.02	0.1	0.03	0.1
30-Jul-97	0.02	0.02	0.014	0.03	0.04	0.02	0.1	0.01	0.02	0.85	0.008	0.86	0.1	0.03	0.01	0.03	0.02	0.1	0.03	0.1

Sample site 13		Pesticides - total	pH	Phenol	Phosalone	Polychlorinated Biphenyls	PP - DDE	PP - DDT	Prometryne	Propazine	Propetamphos	Propham	Propiconazole	Propyzamide	Quintozene	Simazine	TDE (PP)	Tecnazene	Terbutylazine	Terbutryne
23-Oct-96	8.4	0.05	8.3	0.1	0.02	0.026	0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
30-Oct-96	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
06-Nov-96	7.8	0.05	8.1	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
13-Nov-96	8.3	0.05	8.1	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
20-Nov-96	8.1	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
27-Nov-96	8.2	0.05	8.1	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
04-Dec-96	8.1	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
11-Dec-96	8.2	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
18-Dec-96	8.3	0.05	8.3	0.1	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
03-Jan-97	8.4	0.05	8.4	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
08-Jan-97	8.4	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
15-Jan-97	8.2	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
22-Jan-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
29-Jan-97	8.4	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
06-Feb-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
12-Feb-97	7.7	0.05	7.7	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
26-Feb-97	8.1	0.05	8.1	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
05-Mar-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
12-Mar-97	8.5	0.05	8.5	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
19-Mar-97	8.1	0.05	8.1	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
26-Mar-97	8.7	0.05	8.7	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
02-Apr-97	8.6	0.05	8.7	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
07-Apr-97	8.7	0.05	8.7	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
16-Apr-97	8.5	0.05	8.5	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
23-Apr-97	8.5	0.05	8.5	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
30-Apr-97	8.6	0.05	8.6	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
07-May-97	8.2	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
14-May-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
21-May-97	8.5	0.05	8.5	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
28-May-97	8.5	0.05	8.5	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
04-Jun-97	8.5	0.05	8.5	0.18	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
11-Jun-97	7.9	0.05	7.9	0.13	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
18-Jun-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
25-Jun-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
02-Jul-97	8.3	0.05	8.3	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
09-Jul-97	8.2	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
16-Jul-97	8.4	0.05	8.4	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
23-Jul-97	8.2	0.05	8.2	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02
30-Jul-97	8.4	0.05	8.4	0.1	0.02		0.01	0.01	0.02	0.02	0.02	0.05	0.02	0.02	0.002	0.02	0.01	0.01	0.02	0.02

Sample site 13		Total Ammonia	Total Coliforms	Thiamimelton	Triallate	Trisazophos	Triolopyr	Therazane	Thimurellin	Turbidity
23-Oct-96	0.03	1840	0.02	0.02	0.03	0.02	0.02	0.01	0.01	1.35
30-Oct-96	0.03	1920	0.02	0.02	0.03	0.02	0.02	0.02	0.01	2.41
06-Nov-96	0.03	2840	0.02	0.02	0.03	0.02	0.02	0.02	0.01	10.9
13-Nov-96	0.03	390	0.02	0.02	0.03	0.02	0.02	0.02	0.01	2.14
20-Nov-96	0.05	6000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	5.6
27-Nov-96	0.03	270	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.81
04-Dec-96	0.03	900	0.02	0.02	0.03	0.02	0.02	0.02	0.01	3.45
11-Dec-96	0.03	5	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.64
18-Dec-96	0.03	700	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.11
03-Jan-97	0.03	390	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.7
08-Jan-97	0.03	270	0.02	0.02	0.03	0.02	0.02	0.02	0.01	2.08
15-Jan-97	0.03	120	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.22
22-Jan-97	0.03	680	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.68
29-Jan-97	0.03	19	0.02	0.02	0.03	0.02	0.02	0.02	0.01	2.71
05-Feb-97	0.03	180	0.02	0.02	0.03	0.02	0.02	0.02	0.01	2.83
12-Feb-97	0.03	5000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	20
26-Feb-97	0.03	20000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	7
05-Mar-97	0.03	340	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.5
12-Mar-97	0.03	300	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.34
19-Mar-97	0.03	1000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	4.96
26-Mar-97	0.03	320	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.68
02-Apr-97	0.03	530	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.51
07-Apr-97	0.03	780	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.81
16-Apr-97	0.03	490	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.23
23-Apr-97	0.03	11	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.12
30-Apr-97	0.03	260	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.08
07-May-97	0.03	1200	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.85
14-May-97	0.03	330	0.02	0.02	0.03	0.02	0.02	0.02	0.01	2.3
21-May-97	0.03	180	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.3
28-May-97	0.03	190	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.58
04-Jun-97	0.03	160	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.44
11-Jun-97	0.12	24000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	5.4
18-Jun-97	0.03	680	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.3
25-Jun-97	0.03	2660	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.52
02-Jul-97	0.03	2000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.22
09-Jul-97	0.03	1300	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.2
16-Jul-97	0.03	28000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.75
23-Jul-97	0.03	530	0.02	0.02	0.03	0.02	0.02	0.02	0.01	1.11
30-Jul-97	0.03	840	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.86