Groundwater Pollution Research Reviews

A Briffett, L Houlden, S Kirk, A McMahon, P Miles, R Stephenson, E Walker

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Geraghty & Miller International, Inc.

Environment Agency
Rivers House
Waterside Drive
Aztec West
Bristol
BS12 4UD

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Environment Agency
Rivers House
Waterside Drive
Aztec West
Bristol
BS12 4UD

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Statement of Use
This document provides a series of reviews of areas of current research in Groundwater Pollution. Its primary purpose is to provide an introduction to the Technical Literature for the benefit of Agency staff, who do not have a specialist background in hydrogeology.

Research Contractor
This project was produced under R&D Project i623 by:

Geraghty & Miller International, Inc
Conqueror House
Vision Park
Histon
CAMBRIDGE
CB4 4ZR

Tel: 01223 236950 Fax: 01223 236242

Environment Agency's Project Manager
The Environment Agency Managers for R&D Project i623 were:

Dr Bogus Zaba & Richard Boak

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KEY WORDS

Aquifer, attenuation, biodegradation, bioremediation, contaminated land, contamination, groundwater, groundwater pollution, intrinsic bioremediation, landfill, landfill leachate, pollution, radioactive waste, radionuclides, remediation, source protection, vulnerability

GLOSSARY

Absorption	Process by which solute diffuses into porous aquifer particles to be sorbed onto interior surfaces.
Acidification	Acidic deposition from the atmosphere.
Adsorption	Process by which a thin layer of a substance accumulates on the surface of a solid.
Aliphatic	Of or pertaining to a broad range of organic carbon compounds characterised by straight or branched open-chain arrangement of the constituent carbon atoms. The carbon-carbon bonds may be saturated or unsaturated.
Aromatic	Of or pertaining to organic chemicals that resemble benzene in chemical behaviour.
Attenuation	Any process which reduces the concentration of contaminants in sub-surface soil and groundwater environments.
Bioaccumulate	Process by which contaminants build up in the food chain.
Bioaugmentation	Strictly, the introduction of non-indigenous micro-organisms for bioremediation or for enhancement of bioremediation with indigenous micro-organisms. The term could also include the use of enrichment micro-organism cultures derived from the local environment.
Biodegradation	A process by which micro-organisms transform or alter by enzymatic action the structure of chemicals into the environment.
Bioremediation	Remediation process which involves the use of micro-organisms to convert contaminants to less harmful species.
Biotic	Of or pertaining to life and living organisms.
Containment (hydraulic)	The use of physical or hydrodynamic barriers to prevent the spread of contaminants through the groundwater.
Contamination	Artificially induced degradation of natural groundwater quality.
Diffuse source pollution	Pollution from widespread activities with no one discrete source.
Directive	A type of legislation issued by the European Community which is binding on member states in terms of the results to be achieved.

Drift deposits	Term used to include all unconsolidated superficial deposits overlying solid rock.
Fractures/fissures	Natural cracks in rocks that enhance rapid water movement.
Hazard	A situation or object with potential to cause harm.
Hydrocarbon	A large group of chemical compounds composed only of carbon and hydrogen. Derived from petroleum crude oil or coal, natural gas, and other natural and anthropogenic sources.
Intrinsic bioremediation	The use of natural destructive biodegradation processes to reduce the mass, mobility and associated risks of contaminants in soil and groundwater.
Intrinsic remediation	The use of combined effect of natural destructive and non-destructive processes to reduce the mass, mobility and associated risks of contaminants in soil and groundwater. Non-destructive processes include dilution, volatilisation and sorption. Destructive processes include aerobic and anaerobic biodegradation and chemical transformation reactions such as precipitation and hydrolysis.
Landfill	Site used for waste disposal into/onto land.
Leachate	The liquid that has percolated through solid waste or contaminated soil and dissolved soluble components.
Natural bioremediation	See Intrinsic Bioremediation.
Outcrop	Where geological rock strata are at the surface, even though they may be obscured by soil or drift cover.
Permeability	Measure of the ability of a medium to transmit water.
Point source pollution	Pollution from a discrete source e.g. petrol station, septic tank, landfill.
Pollution	When the degree of contamination, with respect to a certain substance, reaches a point beyond which the groundwater becomes unsuitable for a given purpose (e.g. as drinking water).
Porosity	Ratio of void space to the total volume of the rock.
Recharge	Water which percolates downward from the surface into groundwater.

Refractory	A non-specific characteristic of some chemicals implying resistance to biodegradation or other degradation or treatment process.
Remediation	Restoration of soil and/or groundwater quality sufficient to permit required use.
Residual saturation	Saturation below which fluid drainage will not occur.
Risk	Expresses the likelihood that the harm for a particular hazard is realised.
Risk assessment	Characterisation of the potential adverse effects of exposure to a hazard.
Saturated zone	Zone of aquifer where all fissures and pores contain water (i.e. below the water table).
Septic tank	Small tank receiving and treating sewage by bacteria where effluent overflows.
Soakaway	System for allowing water or effluent to soak into the ground, commonly used in conjunction with septic tanks.
Sorption	A general term used to include absorption, adsorption, ion exchange and chemisorption.
Sorption processes	Includes adsorption, chemisorption, absorption and ion exchange processes.
Source	Point of abstraction of water e.g. well, borehole, spring.
Unsaturated zone	Zone of aquifer between soil and watertable which is partly saturated (i.e. that part of the aquifer above the water table.)
Vadose zone	Synonomous with unsaturated zone.

1. INTRODUCTION

1.1 Project Objectives

1.1.1 Overall Objectives

The overall objective of EA R&D Project i623 is:

- To provide Environment Agency (EA) staff with up-to-date reviews of research in the areas of groundwater pollution and bioremediation research, which are developing rapidly and in which operational staff have difficulties in keeping abreast of developments.

1.1.2 Specific Objectives

The specific objectives of EA R&D Project i623 are:

1. To disseminate information on general research in groundwater pollution to field staff in order that the Environment Agency, is, and is seen to be, a well informed, professional body.

2. To provide specialist advice on bioremediation technology for groundwater amelioration, especially in terms of assessing suitability of contaminated sites for the application of these techniques and to make recommendations to the EA regarding development of some expertise in these technologies.

1.2 Scope of this Report

This report presents the findings of the review of groundwater pollution research, relating to Objective 1 in Section 1.1.2 above.

The findings of the review of current and recent research in bioremediation technology relating to Objective 2 in Section 1.1.2, are reported in a separate report (EA Technical Report P3).

1.3 Background

A significant amount of UK research on groundwater pollution is funded by external agencies, outside the EA. Operational staff within the EA are generally not exposed to the results of this work and there is a need to improve the dissemination of research information. Geraghty & Miller International, Inc. (G&M) were commissioned by the EA to undertake a review of recent research into groundwater pollution, both completed and in hand, and compile this summary R&D document intended for circulation to EA operational staff. This document will improve the dissemination of information resulting in better informed decision-making by field staff.

1.4 Approach

The specific topics of groundwater pollution which are discussed were selected from a number of groundwater issues identified in a report published by the Foundation for Water Research, (FWR, 1995)[1]. The FWR report looks at what is known, what is not known, and what needs to be known about the groundwater resources of the UK. It identifies issues affecting both groundwater quantity and quality. The key groundwater quality issues (excluding nitrates and saline intrusion) were selected for inclusion in this document. Some related topics have been grouped where appropriate.

The information for this study was compiled from a number of sources. References from open literature were retrieved from databases using library search techniques (e.g. BIDS Database). Information on research projects was obtained from published lists (e.g. CRIB, Resline), and directly from the funding organisations. Further data were obtained by sending out a questionnaire to research institutions. All data were compiled in an ACCESS database which was then searched for information on each of the topics discussed in the following sections. A list of individuals and organisations contacted in the literature survey is presented in Appendix A.

This document reports the information obtained as a result of the searches described above, and the aim has been to report the recent (generally within the last 5 years) and current research situation as it affects groundwater pollution. The report is not intended to be a textbook and is not a comprehensive guide to all aspects of the issues discussed. Certain topics may not be the subject of recent investigation, and there may also be gaps in the data where questionnaires have not been returned, or requests for information have been refused.

1.5 Organisation of this Report

Section 2 of this report is divided into subsections covering 14 groundwater pollution issues.

For each issue there is a page which gives an overview of the issue, a list of relevant recent and current research projects in the UK with the status and contact point for each, and a list of the key references relating to the issue in the UK. The subsequent text in each subsection discusses the groundwater pollution issue in more depth, and where appropriate, key information is enclosed in highlighted boxes. The text is followed by a listing of additional references, and where necessary, a listing of additional research projects.

[1] FWR. (1995). Groundwater in the UK: A Strategic Study - Issues and Research Needs. FR/GF 1, Foundation for Water Research, Liston Rd, Marlow, Bucks, UK.

2.1 Acidification

Overview

Acidified precipitation ('acid rain') is a recognised and widespread phenomenon in the UK. A large amount of work has been done on its effect on surface waters. The effects of acid deposition on groundwater are considered to be small. Other sources of acid in groundwater include: natural water-rock interaction; contamination with industrial acids; and degradation of other contaminants. However, groundwater acidification has not been considered a research priority as most major aquifers are well-buffered and most UK groundwaters are alkaline. Where lowering of groundwater pH does occur it increases the solubility of metals. Resources likely to be affected are small, shallow private supplies which are not treated.

Recent / Current Research Projects	Status and Contacts
• The Susceptibility of UK Groundwater to Acid Deposition.	• 1986. BGS Hydrogeology Group (most comprehensive study to date).
• Acidification in the Birmingham Aquifer	• 1992. Birmingham University (contact: J. Tellam).
• Development of MAGIC (Model of Acidification of Groundwater in Catchments) and Use in Catchment Modelling.	• 1992. Institute of Hydrology (contact: P. Whitehead).

Key References

Ford, M., Tellam, J.H. and Hughes, M., (1992). Pollution-Related Acidification in the Urban Aquifer, Birmingham, UK. Journal of. Hydrology, **140,** p297-312.

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Tickle, A. (1990). Acid Waters in the United Kingdom: Evidence, Effects and Trends. *In Acid Deposition - Origins, Impacts and Abatement Strategies. J.W. Longhurst (ed.), Springer Verlag*

See also: Acid Mine Drainage

2.1 Acidification

The phenomenon of 'acid rain' has been known for over a century and is caused largely by the release of oxides of sulphur and nitrogen into the atmosphere. The possible environmental impacts of acid precipitation have been recognised in the last 25 - 30 years. Acidic precipitation is widespread in the UK and it is now perceived as a major cause of acidification of surface water. A significant amount of research on the effects of acidification on streams and lakes, their ecology, and on soils has been published and more is ongoing. A recent review is given by Tickle, 1990. In contrast, relatively little work has been done on acidification of groundwater, with the exception of one major British Geological Survey review.

In 1986 the Hydrogeology Group of the British Geological Survey published the findings of an investigation carried out at the request of the Department of the Environment (Kinniburgh and Edmunds, 1986). The scope of the study was as follows:

- processes controlling the acidification of natural waters were identified.
- evidence for the acidification of UK groundwaters was reviewed.
- major and minor aquifers and lithologies in the UK most susceptible to acidification were reviewed.
- an assessment was made of both the actual and the potential effect of acid deposition on potable groundwater resources.

The conclusions drawn were that, in general, UK groundwaters are alkaline and well-buffered. The major UK aquifers all contain a significant proportion of calcium carbonate, and in many minor aquifers acidic infiltration will be neutralised by overlying or adjacent less acidic strata. The most important effect of the lowering of groundwater pH is that it leads to increased solubility of metals. The water supplies most at risk from the effects of acidification are small, shallow resources, which are often private, untreated supplies.

A detailed study of water quality in the Sherwood Sandstone aquifer underlying Birmingham was undertaken between 1987 and 1989, by a group led by researchers at Birmingham University. This indicated that pH values of groundwater had fallen by an average of 0.6 pH units since a similar study a decade earlier. Ford, Tellam and Hughes (1992) considered six potential causes and concluded that the most important ones are: spills of inorganic acids, and oxidation and degradation of other pollutants.

Whitehead (1992) describes several models which have been developed for applications such as environmental impact assessments, and which are used by the Institute of Hydrology. These include MAGIC (Model of Acidification of Groundwater in Catchments) which is a model based on mathematical representations of chemical equilibria and mass balance. Ferrier, Whitehead and Miller (1993) used MAGIC to illustrate the potential interactions between land use, acid deposition and climate change in the Monachyle catchment at Balquhidder. This work was part of a wider study of the Balquhidder catchment.

In summary, acidification in groundwater has not been a research priority in the UK in the 1990s. Any work which has been done has generally formed a small part of surface water studies, or wider work on groundwater quality such as the Birmingham study.

2.1 Acidification

References

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Ferrier, R.C., Whitehead, P., Miller, J.D. (1993). Potential Impacts of Afforestation and Climate Change on the Stream Water Chemistry of the Monachyle Catchment. Journal of. Hydrology, **145,** No.3, p453-466.

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Whitehead P., (1992). Examples of Recent Models in Environmental Impact Assessment. Journal of the Institution of Water and Environmental Management, **6**, No.4, p475-484.

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2.2 Acid Mine Drainage

Overview

The closure of many UK mines and the resulting groundwater rebound following the cessation of dewatering has led to several cases where mine water has seriously contaminated surface watercourses. This has provided the impetus for a recent increase in research activity. Current groundwater related research is concentrated in three main areas: i) modelling groundwater rebound and flow in mine workings; ii) adding to the current understanding of minewater hydrochemistry; and iii) developing suitable treatment schemes for mine discharges.

Recent / Current Research Projects	Status and Contacts
• Development of GRAM (Groundwater Rebound in Abandoned Mines) software and application in two Scottish mines.	• 1996, Newcastle University (contact: J. Sherwood).
• Improved Modelling of Abandoned Mines.	• 1996-1999, EA R&D project, (contact S. Aspinwall at Leeds EA).
• Durham Minewater Study.	• 1992-1996 onwards, Newcastle University (contact P. Younger).
• The River Pelenna Minewater Treatment Project: Development of a minewater treatment computer design package.	• 1995 - 1997, EA funding, (contact: C Bolton and P Edwards at the Welsh Region EA).
• Pilot test and full scale minewater treatment plant construction for discharges from Sheephouse Wood mine, South Yorkshire.	• 1993-1996, EA funding, (contact L Bird at EA North East). Pilot scale complete and full scale system in design stages.
• Minewater Treatment Plant Pilot Scheme at Wheal Jane Mine, Cornwall.	• 1996, EA and DoE funding (contact E Drury at the EA, Bodmin).

Key References

Bird, L. (1994). Assessing Cost Treatment Technologies for Discharges from Disused Mines. *In Proceedings of BICS International Conference on Managing Abandoned Mine Effluents and Discharges, (1994).*

Younger, P.L., Barbour, M.H., and Sherwood, J.H. (1995). Predicting the Consequences of Ceasing Pumping from the Frances and Michael Collieries, Fife. *In Proceedings of the 5th International Hydrology Symposium, (1995).*

Younger, P.L. (1995a). Hydrochemistry of Minewaters Flowing from Abandoned Coal Workings in County Durham. Quarterly Journal of Engineering Geology, **28**, p101-113.

See also: Acidification

2.2 Acid Mine Drainage

Acid mine drainage has been tolerated in UK mining areas for hundreds of years. However, the decline of the mining industry in the 1980s and 1990s has resulted in an increase in the scale of the problem. As groundwater ceases to be pumped from old workings the rising water comes into contact with oxidised minerals, mainly pyrite. The groundwater becomes acidic and contaminated with metals and sulphate. On mixing with fresh water, characteristic bright orange precipitates of iron hydroxide are produced. Minewater discharges can have devastating effects on aquatic life, are visually conspicuous and reduce the amenity value of affected watercourses. The areas affected are often those with a long history of poor water quality.

Acid mine drainage has become an active field of research in the UK in the 1990s. For obvious reasons the work tends to be geographically concentrated in areas with an extensive coal or metal mining history, notably Durham, Yorkshire, southern Scotland, Cornwall and Wales. A wide range of organisations sponsor research in acid mine drainage, including local authorities, the water industry, the Environment Agency, River Purification Boards, Department of the Environment, British Coal, the Coal Authority, and private companies.

Most current UK research into acid mine drainage can be considered under three sub-divisions. i) Hydrogeological modelling of groundwater rebound and flow within mine workings. ii) Hydrochemical studies of minewater. iii) Development and testing of pilot and full-scale treatment schemes for minewater discharges.

BOX 1: Current and Recent Research on Hydrogeological Modelling of Acid Mine Drainage.

- Dussek (1992) and Bowen & *et al* (1994) describe how a 'water-balance' approach was used to develop a conceptual model of groundwater flow in the flooded Wheal Jane tin mine in Cornwall.. Further catchment modelling is proposed for 1996.

- Sizer (1994) describes the application of two existing groundwater modelling packages, AQUA and MODFLOW to create 2D and 3D flow models of the Durham coalfield.

- Software known as GRAM (Groundwater Rebound in Abandoned Mines) has been developed at Newcastle University, and used to model flow in the Frances and Michael mines, deep coal mines in East Fife. This work has been carried out as a PhD thesis by J. Sherwood, funded by the Forth River Purification Board, and is due to be completed in October 1996.

- 'Improved Modelling of Abandoned Mines' is a three year research contract jointly funded by the EA and North-East Water, recently awarded to Newcastle University. This study began in January 1996, and aims to develop models of conduit networks interspersed in a matrix allowing Darcian flow.

- A study commissioned by the Coal Authority and being carried out by Scott Wilson Kirkpatrick and the University of Nottingham involves monitoring 30 minewater discharges throughout the UK. Measurements mainly involve the quantity of the outflows, work on their quality is limited. The focus of the study is to assess the stability of the mine workings and the risk of ground subsidence in a regime of groundwater rebound.

2.2 Acid Mine Drainage

Abandoned mine workings are complex to model as they consist of large open conduits, set in strata which are typically of low permeability and in many cases fractured. There are often vast areas of interconnected workings, and mine plans can be extremely complex or non-existent in the case of very old workings, or rendered inaccurate by collapse within the mine. In some cases a 'water balance' approach has been used as a simpler alternative to the use of computer modelling. However, additional suitable software is now being developed for this specific application. Current and recent research on hydrogeological modelling is presented in Box 1.

The chemical process in which mine waters dissolve oxidised pyrite to become acidic and rich in iron and heavy metals is well understood. The basic chemical reactions are widely documented in published literature including Robb (1994), Sizer (1994), Younger (1995a). Chemical speciation models such as PHREAQ and NETPATH have been used to model chemical changes in minewater discharge, as part of the Durham Minewater Study conducted by Newcastle University, Younger (1995a). The results enable possible future river pollution to be predicted and treatment schemes to be planned and a new classification scheme for minewaters was proposed. At present the British Geological Survey & the Scottish Rivers Purification Board are proposing a joint investigation into the chemical changes of mine discharges with time. This study will involve an analysis of discharges from abandoned mines of different ages throughout Scotland.

In addition to the research in hydrological modelling and chemistry of minewaters, several pilot

BOX 2: Minewater Treatment Case Studies.

- **Sheephouse Wood, South Yorkshire:** A pilot plant for active treatment was constructed, and operated from January to July 1993. Treatment involved addition of alkali and flocculant; filtration on gravel pads; air drying and resettling. A full-scale plant was designed and costed, and funding is being sought for its construction. (Contact: Linda Bird, EA North East)

- **Wheal Jane, Cornwall:** A temporary treatment scheme is in operation involving pumping discharge into an existing tailings dam at the mine for treatment. A pilot plant has been constructed to test methods of passive treatment. After one of three alternative pre-treatments the water passes through an aerobic cell (reed beds) to remove iron, arsenic and acidity; an anaerobic cell (cattle manure and sawdust) to remove cadmium, zinc, copper and sulphate, and finally a rock filter to remove manganese. A further pilot scheme for active treatment, and methods for reducing infiltration into the workings are under consideration. Work is funded by the Environment Agency and the Department of the Environment. (Contact: Elaine Drury, EA Bodmin)

- **River Pelenna, South Wales:** An area of approximately 20,000m^2 of reed beds is being constructed at five wetland sites in order to remove metals from discharges from several mines in the Tonmawr area. Additional passive treatment techniques such as limestone drains or lagoons will also be used in some cases. (Contact: West Glamorgan County Council: Dept. Environment and Highways). As part of the River Pelenna Minewater Treatment Project, the EA Welsh region is funding the development of a minewater treatment computer design package. This work began in April 1995 and is due for completion in February 1997.

schemes to develop cost-effective methods of treating mine discharges have been carried out. Most approaches involve either active treatment or passive treatment of minewater on the surface. Active treatment involves addition of chemicals such as alkali or flocculant to the discharge. Examples of passive treatment techniques include settlement lagoons and treatment in specially constructed reed beds, in which pH is increased by biological action at root level. Other treatment schemes include lime dosing in mine shafts, and various methods of restricting groundwater flow into workings. Three recent case studies are outlined in Box 2.

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2.2 Acid Mine Drainage

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2.3 Contaminated Land

Overview

Industrial activity has left land contaminated with a variety of inorganic and organic contaminants, frequently including heavy metals, hydrocarbons, and organic solvents, which can lead to serious groundwater pollution. The historical problem is widespread, but recent legislation governing industrial processes and emissions seeks to reduce future contamination. In comparison with other countries, particularly the US, UK experience in the remediation of groundwater polluted by contaminated land is limited. Extensive research has recently been initiated in the UK to develop a contaminated land policy in which risk/site assessment procedures, remedial treatments and the impact of contaminated land on groundwater are being studied.

Recent / Current Research Projects	Status and Contacts
• Research into the Impact of Contaminated Land on the Water Environment.	• Dec 1995 - Final draft at review. DoE, CLR Programme (Research Project Ref. 41). Prepared by Sir William Halcrow (Contact C Hoggart).
• Modelling the Impact of Contaminated Land on Water Quality using the MIKE-SHE Model.	• Dec 1995 - Final draft at review. DoE, CLR Programme (Research Project Ref. 42). Prepared by WS Atkins (Contact: R Gray).
• A Framework for Assessing the Impact of Contaminated Land on Groundwater and Surface Water.	• Completed 1994. DoE (1994a), prepared by Aspinwall & Company.
• Pollution Potential of Contaminated Sites-Phase 2.	• 1994 - 1996. EA R&D Project A08(94)5. (Contact: J Thomas, Thames).
• Development on Contaminated Land - Phase 3.	• 1994 to 1996. EA R&D Project A14(91)3 - 380. Prepared by CIRIA (Contact: B Harris (EA, Midlands))
• Core Programme Remedial Treatment of Contaminated Land Phases I, II & III	• Dec 1995 - Phases I and II complete, Phase III ongoing. Prepared by CIRIA, (Reports SP101 to 112).

Key References:

DoE. (1994a). A Framework for Assessing The Impact of Contaminated Land on Groundwater and Surface Water. CLR Report No.1 (2 Vols).

DoE (1994b). Guidance on Preliminary Site Inspection of Contaminated Land. CLR Report No. 2 (2 Vols).

DoE (1994c). Sampling Strategies for Contaminated Land. CLR Report No. 4 (2 vols).

DoE (1995). Prioritisation and Categorisation Procedure for Sites which may be Contaminated. CLR Report No 6 (2 vols).

ICE (1994). Contaminated Land: Investigation Assessment and Remediation; ICE Design and Practice Guides.

Institute of Petroleum (1992). Code of Practice for the Investigation and Mitigation of Possible Petroleum Based Land Contamination.

See also: Remediation

2.3 Contaminated Land

It is estimated that there are around 50,000 hectares of contaminated land in the UK. Contaminated land presents a groundwater pollution risk if contaminants can migrate into the aquatic environment, and persist at potentially harmful concentrations. In the UK contaminated land is a major source of groundwater pollution. The legacy of contamination resulting from past and present anthropogenic activities has led and will continue to lead, to serious groundwater pollution incidences (Tellam, 1994; Lerner and Tellam, 1992).

Contaminated land has been the subject of a number of extensive research programmes, funded by both government and industrial establishments (e.g. DoE, EA, ICE and CIRIA). The Department of the Environment (DoE) is currently running the Contaminated Land Research (CLR) Programme. The programme is designed to support the development of contaminated

BOX 1: Recently Published GUIDANCE DOCUMENTS on Contaminated Land

CLR Report No. 1 (1994) *A Framework for Assessing the Impact of Contaminated Land on Groundwater and Surface Water*

Vol. 1: General overview of the risk posed by contaminated land to water, and guidance on the selection of assessment framework, impact assessment and techniques for predicting impacts.

Vol. 2: Detailed annexes including; contaminants and their control, guidance for assessing contamination in water, review of systems assessing groundwater and surface water pollution, guidance sheets, assessment plans and review of computer models.

CLR report No 2 (1994) *Guidance on Preliminary Site Inspection of Contaminated Land.*

Vol. 1: Site manual, including a check list and assessment forms.

Vol 2: Reference text containing information on, and reviews of, relevant literature on major contaminants and associated abiotic or biotic indicators.

CLR report No 4 (1994) *Sampling Strategies for Contaminated Land*

Guidance for designing a sampling strategy (number and location of sampling points, and sample depths) for sites where contamination is known or suspected.

CLR report No 6 (1995) *Prioritisation and Categorisation Procedures for Sites which may be Contaminated*

Presents a simple, systematic approach to prioritise actions, including; desk top studies, site investigations, site specific risk assessments and remedial strategy development, at contaminated sites.

CIRIA reports SP101 to SP 112 *Remedial Treatment of Contaminated Land*

Phase I: 12 vol. report, documenting guidance for decommissioning, site characterisation, remedial selection, implementation and closure.

Phase II: A set of state of the art reviews on remedial technologies.

Phase III: (research in progress) Includes reviews of a number of case studies, comparing remedial technologies in use in the EC.

ICE Contaminated Land: Investigation and Remediation: ICE Design and Practice Guides (1994).

land policy by improving understanding of the problems and evaluation of solutions. The work underpins government legislative regimes to deal with threats to the environment, whilst assisting the objective of bringing such land back into beneficial use. Work conducted under the CLR programme has led to the publication of a number of guidance documents, mainly focused on assessment procedures. The Construction Industry Research and Information Association (CIRIA) has also recently produced a set of reports, under '*The Remedial Treatment of Contaminated Land*' project. The project work is divided into three phases, phases I and II are complete and phase III is ongoing. The reports provide general guidance on assessing contaminated land and developing remedial solutions complimentary to the DoE reports. Details of the DoE and CIRIA recently published guidance documents are given in Box 1.

Following the identification of contaminated land sites, determination of the potential risks posed by the site is vital before proceeding with extensive site investigation or remedial activity. Risk assessment methodologies have received a great deal of attention in recent years and a variety of approaches has been developed (Henton and Young, 1993; Walker *et al.*, 1994; Cole *et al*, 1994). The guidance documents produced by both CIRIA and the DoE have helped to clarify risk assessment and general site investigation techniques.

Current research on contaminated land is abundant. The majority of work is funded by the DoE, CLR programme. Current projects under the CLR programme are listed in Boxes 2 and 3. Projects include the development of further guidance documents on exposure assessment,

BOX 2: Current Research Projects on RISK / IMPACT ASSESSMENT and SITE INVESTIGATION under the DoE Contaminated Land Research Programme, (Due for completion in early 1996).

- *The Contaminated Land Exposure Assessment Model (CLEA) Technical Basis and Algorithms* (Research Project (RP) Ref. 17.). Prepared by Nottingham Trent University.
- *Generic Guideline Values for Contaminants in Soils* (RP Ref 32/58). Prepared by Nottingham Trent University.
- *Priority Contaminants* (RP Ref PC/100). Prepared by Environmental Sciences Ltd.
- *Design of Sampling Strategies for Site Investigation (Expert Systems)* (RP Ref. 39). Prepared by Nottingham Trent University.
- *Review of Test Methods for Contamination in Soil* (RP Ref. 15). Prepared by HB Berridge & Partners, ACER, MJ Carter Associates and Clayton Env. Consultants.
- *Collation of Toxicological Data* (RP Ref. 19/21/51). Prepared by RPS Group plc.
- *Research into the Impact of Contaminated Land on the Water Environment* (RP Ref. 41). Prepared by Sir William Halcrow & Partners Ltd.
- *Modelling of Impact of Contaminated Land on Water Quality using MIKE-SHE model* (RP Ref. 42). Prepared by WS Atkins Consultants.

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clean-up criteria, strategies for sampling and site investigation and assessment, and research on different remedial treatment options. The EA is also developing methodologies to define clean-up standards for soils to protect the water environment and for polluted groundwater (see REMEDIATION).

The impact of contaminated land on groundwater is a serious problem, and one in which the processes are not fully understood. Current work on this topic includes CLR project 41 which reviews the legislative and regulatory background, contaminant sources, investigation and assessment procedures and remediation for contaminated land impacts on groundwater. Research on the prediction of groundwater quality impacts using the MIKE-SHE model has also been completed recently (CLR Project 42).

Work on the evaluation of remedial treatments for contaminated land is an emerging research area. Expertise in this area has traditionally been concentrated abroad (USA, the Netherlands and Germany). However increasingly stringent legislation and identification of the risks presented by contaminated land have highlighted the need for remedial treatment in the UK. A review of recent developments in contaminated land treatment technology is given by Bardos (1994) and Bardos and van Veen (1996). Current research identified in this study includes DoE CLR projects (see Box 3) which cover reviews of available soil treatment technologies, performance evaluations and monitoring techniques. State of the art reviews of relevant treatment technologies and case study examples are included under Phases II and III of the CIRIA programme.

In general, future research on contaminated land is required to improve the understanding of the impact on groundwater quality, in order to classify risk and identify mitigation strategies (FWR, 1995). This involves collection of data on the extent of groundwater pollution from contaminated land, monitoring of the effectiveness of remediation procedures, and a better understanding of the processes which control and influence the nature and extent of pollution.

BOX 3: Current Research Projects on REMEDIAL TREATMENT under the DoE Contaminated Land Research Programme, (Due for completion in early 1996).

- *Guidance for Evaluating the Performance of Remedial Measures for Contaminated Land* (RP Ref. 30). Prepared by CH2M Hill UK Ltd.
- *Investigation of Combined Treatment and Containment Systems: Review of Approaches and Identification of Low Cost Combinations* (RP Ref. 56). Prepared by Golder Associates.
- *Investigation of Enhancement Techniques for Ex-situ Soil Separation Processes, Particularly with Regard to Fine Particles: Critical Review and Experimental Study* (RP Ref. 52). Prepared by AEA Technology.
- *Review of Research on Process Technologies for Remediation of Contaminated Land* (RP Ref. 45). Prepared by Nottingham Trent University.
- *Evaluation of Monitoring Techniques and Technologies for Contaminated Land* (RP Ref. 28). Prepared by Hunting Land & Environmental Ltd.

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2.4 Heavy Metals

Overview	
Heavy metals are commonly present in UK groundwater at trace concentrations. The most common sources of contamination include mining, urban and industrial effluents, agricultural wastes, sewage sludge, fertilisers and fossil fuels. Heavy metals can be extremely toxic to humans even at low concentrations, due to a tendency to bioaccumulate in the food chain. However, high concentrations in aquifers are not normally a problem as heavy metals are generally relatively insoluble in groundwater under normal pH conditions (6.5 to 8.5), and are therefore immobile in most UK aquifers. The greatest risk posed by heavy metal contamination is in shallow, acidic groundwaters.	
Recent / Current Research Projects	**Status and Contacts**
• Heavy Metal Transport in Water and Soils	• 1995 - 1998, JD Donaldson, SM Grimes (and postdoctoral research fellows) at Brunel Uni, Dept. of Chemistry.
• Heavy Metal Removal by Electrodeposition and Liquid Membranes.	• 1993 - 1996, EPSRC funding, Prof K Scott at University of Newcastle, Dept of Chemical and Process Engineering.
• Removal of Toxic Metals from Water and their Recovery as Metals by Biosorption, Elution and Electrolysis.	• 1996 - 1999, EC funding, IC Hancock, L Evison (University of Newcastle, Dept of Microbiology) and colleagues in Portugal and Greece.
• Remediation of Contaminated Land by Inducing the Formation of Heavy Metal Phosphates.	• 1995, Dr J Cotter-Howells, University of Aberdeen, Dept of Plant and Soil Science.
• Relationships Between Plant Growth and Speciation of Heavy Metals.	• 1995, 3 projects, Dr J Cotter-Howells, University of Aberdeen, Dept of Plant and Soil Science
• Generic Guidance Values for Contaminants in Soils, including Heavy Metal Concentrations.	• 1996, Prepared by Nottingham Trent University, DoE Research Project 32/58.
• Vulnerability of Soils to Pollution by Heavy Metals.	• 1995 - 1997, consortium of MAFF, ADAS, WRc and Reading University funding, contact: Prof Alloway (Reading University).
• Speciation and Bioavailability of Arsenic And Cadmium.	• 1996, BBSRC PhD Studentships, contact: Prof Alloway (Reading University).
• An integrated geoenvironmental survey of Wolverhampton area, combining current and former land use information with geological, hydrgeological and geochemical data using a GIS System.	• 1993 - 1996, BGS Core Programme Project, Dr Paul Hooker, Fuid Process Group

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See Also:

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In the past there has been considerable interest in the fate of heavy metals as a result of sewage sludge application on agricultural land and leaching from landfill sites. Additional sources of heavy metals include metalliferous mining and smelting works, fossil fuel combustion, metallurgical, electronic and chemical industries, warfare and military training, and sports shooting. In recent years recognition of the potentially toxic effects and long term persistence of heavy metal contaminants has focused attention on soil and groundwater protection.

Guideline values for heavy metals in contaminated soil and groundwater have been introduced in Germany, the Netherlands and Canada. As yet no limits have been set for heavy metal concentrations in groundwater in the UK and reference to the Dutch Groundwater Quality Guidelines (target and intervention concentrations) is usually made (see Box 1). These were not based on a separate risk assessment for groundwater, but were derived from the values for soils. They should therefore be treated with caution.

Guidance on the derivation of guideline values for soil contaminants (including heavy metals), is expected to be published by the DoE in the summer of 1996. The report is the result of research at Nottingham Trent University identifying pathways via which target populations can be exposed to contaminants released from, and present on, contaminated land. The project also included the development of a simulation model to identify exposures and intake/doses based on varied concentrations of contaminants in soils, (DoE Project 32/58, contact: J Denner, Contaminated Land and Liabilities Division, DoE). These were not based on a separate risk assessment for groundwater, but were derived from the values of soils. They should therefore be treated with caution.

Box 1: Dutch Groundwater Quality Guidelines (ug/l)

Metals	*Target Value*	*Intervention Value*
arsenic	10	60
barium	50	625
cadmium	0.4	6
chromium	1	30
cobalt	20	100
copper	15	75
mercury	0.05	0.3
lead	15	75
molybdenum	5	300
nickel	15	75
zinc	65	800

The occurrence of heavy metal contamination in UK aquifers is largely undefined. Trace metal data are available for most UK groundwaters (Edmunds *et al*, 1989) but the database is selective and far from complete. More complete data is available in local areas. Recent investigations in Birmingham have revealed isolated hot spots of heavy metal contamination in shallow groundwaters, in and around former metal working areas (Ford and Tellam, 1994). The general lack of contaminant distribution data is likely to change in the near future, driven by increasing environmental regulatory pressures and increasingly frequent detections of heavy metals in groundwater. A pilot study has been carried out by BGS to evaluate the use of a GIS System to combine current and former land use data with environmental data (geology, hydrogeology, geochemistry, water quality) in the Wolverhampton area, Bridge *et al*, 1996, (in press).

The behaviour and mobility of trace metals in groundwater has been the subject of a growing number of research projects in the last decade. A detailed knowledge of the effects of pH and Eh conditions on the solubility and sorption behaviour, particularly to organic matter, clay minerals, hydrous iron and manganese oxides, has been developed. Current work is in progress at Brunel University, Dept of Chemistry (contacts: Prof. J.D. Donaldson and Dr S.M. Grimes), and Reading University, Dept of Soil Science (contact: Professor Alloway)

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Remediation of heavy metal contamination is an emerging area of research. The majority of the current work is focused on methods of removing heavy metals from water and soil. Application to groundwater remediation is an extension of the work conducted in the wastewater treatment industry. Barton *et al*, 1994, discuss the current thinking on remediation of heavy metal contaminated media. The Department of Plant and Soil Science at the University of Aberdeen is actively researching the removal of heavy metal contaminants from soil using hyperaccumulator plants (contact: Dr J. Cotter-Howells).

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2.5 Landfill

Overview
Landfill leachate is potentially highly contaminative to groundwater. With over 4000 active landfill sites in the UK, some existing since the 1970s, there is concern over the pollution threat posed to groundwater. The first landfills operated on the principle of dilute & disperse, and early research indicated little evidence of any deterioration in groundwater quality related to this landfill strategy. However, concerns arose that certain hydrogeological conditions together with certain waste types could result in groundwater contamination. Legislative pressure in the mid to late 1980s brought about changes in landfill practices and requirements for containment. Recent studies have begun to question some aspects of the containment methodology and its ability to protect the groundwater environment.

Recent / Current Research Projects	**Status and Contacts**
• Effects of Old Landfill Sites on Groundwater Quality - Phase 1.	• 1994-1995. EA R&D Project A08(94)2, (contact: P Hart at EA Anglian). Phase II to start 1996.
• The Migration and Attenuation of Priority Pollutants in Landfill Leachate	• 1995. EC, DoE and BGS funded. (contact Dr J Gronow at the DoE).
• Red List Substances in Landfill Leachate.	• 1995-1996 EA and DoE funded. (contact B Zaba at EA, Midlands or Dr J Gronow at the DoE).
• Long Term Weathering of Fly Ash and Implications for Groundwater Contamination	• 1991-1995 South Korean and National Power/Powergen funding. (contact DA Spears, S Lee at the University of Sheffield).
• Characterisation of Leachates from Landfill Sites: A Method for Assessing Degradation State	• 1993 to 1996 PhD studentship, partly funded by Devon Waste Management Ltd (contact S.J. Rowland, C Trier, A Revans at the University of Plymouth).
• Long Term Monitoring of Non-Containment Landfills	• 1993-1996 EA R&D project A08(93)11, partly funded by the DoE. (contact RC Harris at EA Midlands).
• Maximising the Attenuation of Leachate by Landfill Liners	• 1990 to 1994. SERC funding, (contact Prof D Lerner at Bradford University.
• A Risk Assessment Methodology for Landfills.	• 1993-1996. EA R&D project A08(93)5, partly funded by the DoE (contact Dr J Gronow at the DoE).

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See also:

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Literature on landfill impacts on groundwater from the last 20 to 30 years has come mainly from studies funded by the DoE landfill research programme and the water industry. This report is mainly concerned with landfill issues specific to groundwater pollution, but many areas of research are interrelated and a broader range of landfill topics are covered in the project and reference lists.

The potential impact of landfills on groundwater quality hinges on the continuing debate between 'dilute & disperse' and 'containment' landfill design strategies. Mather (1991) questions the ability of liners and leachate collection systems to perform over the extended timescales involved in containment methods, a view also expressed by Robinson and Latham (1993). Mather concludes that dilute and disperse should be used where hydrogeological conditions show it to be acceptable, and that rapid waste degradation should be encouraged in containment sites. A number of authors (Mather 1991, Carter 1993, NRA R&D 1995b) conclude that the potential impact of a landfill on groundwater depends on site specific factors (hydrogeology, waste type, site design). This suggests that risk based site assessment may be the most appropriate method for protecting the groundwater environment. Current research funded by the EA and DoE is pursuing a risk assessment methodology for landfills to be completed in 1996.

Compilation of data pertinent to groundwater pollution from existing landfill sites has been the subject of two recent NRA studies. NRA R&D Note 514 developed a generic risk assessment methodology for landfills (NRA, 1995a). A further study NRA R&D Note 569, studied the effects of old landfill sites on groundwater (NRA, 1995b). The project assessed information from 102 landfills on aquifers across the UK, and literature from the past 30 years. Certain common factors were identified between sites where groundwater contamination from landfill had been observed, these are listed in Box 1. It was also noted that the absence of observed contamination at other sites with similar characteristics was most likely to be due to inadequacies in the monitoring network. A number of UK case studies are presented in Box 2 where landfills have resulted in serious groundwater contamination.

Understanding the impact of a landfill on groundwater requires knowledge of the composition of the landfill leachate. In general, leachate composition depends on the waste type, landfill design and practices, analytical procedures and timing. A database of leachate quality from domestic waste landfills has been compiled in a research project run by the DoE (Robinson *et al.*, 1992). The report indicates the occurrence of compounds of environmental significance within leachates. The occurrence of red list substances in leachate is the subject of current research jointly funded by the EA and DoE. Work is also underway at Plymouth University characterising leachate to develop a methodology for assessing landfill degradation state.

BOX 1: Factors Significant in Causing Groundwater Contamination from Landfills (NRA R&D Note 569)

- Site operates on dilute and disperse philosophy.
- Site is located on an aquifer of major importance.
- Groundwater flow mechanism is dominantly fissure flow.
- Unsaturated zone is thin (<5m).
- Formation has low carbonate content and low buffering capacity.
- Leachate generation has been considerable due to high rainfall infiltration or liquid waste disposal.

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BOX 2: UK Case Studies of Groundwater Pollution from Landfill

FOXHALL, SUFFOLK - Situated on Norwich Crag with a minimum unsaturated zone of 2m. Observed deterioration in groundwater quality due to chloride and ammonia. Remedial measures include a groundwater cut-off wall, groundwater treatment, and capping of older phases. (see Palmer & Young 1991, 1992).

VILLA FARM, COVENTRY - Liquid waste lagoon situated on glacial sands and clays. Infilled voids extend below the water table. Geochemical zonation occurs within the saturated zone with reducing conditions close to the site and oxidising conditions in the uncontaminated groundwater. Heavy metals and organic contaminants are attenuated in the saturated zone. (see Barber *et al.* 1981, Williams 1988, Williams *et al.* 1984, 1991).

MAYTON WOOD, NORFOLK - Situated in sand and gravel over the Chalk aquifer. Site originally operated as dilute and disperse but recent phases are contained. All phases are capped. Contaminant plume is diluted by groundwater and nearby river. No significant risk of environmental damage to river but deterioration of water quality in some private groundwater abstractions is anticipated in the future. Remedial measures include predictive modelling and limited pumping. (see Sladen 1995).

Current research on landfill processes is focused on leachate circulation within the landfill, and the migration and attenuation of leachate contaminants (specifically 'priority pollutants') within the aquifer. Landfill processes impacting groundwater occur in three main areas: within the landfill (leachate generation), and within the unsaturated and saturated zones. The issues of concern in these areas are briefly described below.

Leachate generation processes have changed due to changes in waste composition and landfill practices over the last 20 years. Containment sites allow build up of leachate within the landfill and often require complex and expensive leachate management systems. There is also concern that leachate contaminants within these contained sites will take centuries to fall to levels which are not a threat to the environment (Davies and Hammonds 1991). Leachate generation rates are delayed by modern practices such as capping and waste compaction (Williams *et al.* 1991), this delays impacts on groundwater quality but also delays corrective action in landfill design and practice. Robinson and Latham (1993) advocate rapid landfill stabilisation by acceleration of degradation processes and increasing the rate of leaching of contaminants.

Processes within the unsaturated and saturated zones below landfills have been investigated by a number of authors (Williams *et al.*, 1991; Blakey *et al.*, 1993; and Palmer and Young, 1992). Biodegradation, cation exchange, and sorption may all occur within the unsaturated zone to reduce contaminant concentrations. These processes are most effective in aquifers which have a high buffering and cation exchange capacity (e.g. Chalk), but may also be significant elsewhere (e.g. in the Sherwood Sandstone, Blakey *et al.* (1993)). Physico-chemical and biological processes have also been found to provide natural attenuation within the saturated zone.

A significant part of the current research on landfills concerns construction and monitoring. The performance of landfill liners is of particular interest as there is further debate about containment. Recently published papers reviewing landfill design and liner installation include Seymour, 1992; Murray *et al.*, 1992; and Philpott *et al.*, 1992. Research into the attenuation properties of mineral liners has recently been completed and is reported in Bright *et al.*, 1993; and Thornton *et al.*, 1993. Current projects on landfill liner design are listed at the end of this section and include investigations into the performance of geomembranes in aggressive leachate and specific case studies (e.g. Stangate East Landfill, DoE project).

Most of the foregoing references relate to landfilling of mixed household, commercial and non-hazardous industrial waste, which typically contains a significant organic fraction, is biodegradable and is subject to significant long term consolidation settlement due to low initial density and biodegradation effects. However, certain industrial solid wastes are typically landfilled in 'mono-disposal' facilities where only one or possibly two types of waste material are disposed. Examples of these sites are deposits of minerals and mining industry wastes (e.g. colliery shale, coal tailings, quarry fines) and pulverised fuel ash (PFA) from coal-fired power stations. Relatively few references were found on mono-disposal landfilling.

The FWR report (1995) recommends further research on the development of tools for assessment of risk to groundwater from landfills. This will provide information for the design and management of landfills under different hydrogeological conditions. Further work on leachate transport, attenuation, and degradation in UK aquifers is also recommended along with the development of improved monitoring techniques. The DoE has published a number of landfill guidance documents, the most recent of which relate directly to the implementation of Waste Management Regulations under the Environmental Protection Act 1990. The DoE guidance documents which contain groundwater related information are listed in Box 3.

BOX 3:	**DoE Landfill Guidance Documents in the Waste Management Paper (WMP) Series.**
WMP 4	Licensing of Waste Management Facilities
WMP 26	Landfilling Waste
WMP26A	Landfill Completion
WMP 26B	Landfill Design Construction and Operational Practice
WMP 26D	Landfill Monitoring
WMP 26E	Landfill Restoration
WMP 26F	Landfill Co-disposal

Additional Research Projects

A Review of the Composition of Leachate from Domestic Wastes in Landfill Sites. DoE funded research. In preparation in 1995, (contact Dr J. Gronow at the DoE).

Guidance on Good Practice for Landfill Engineering. DoE funded research. In preparation in 1995, (contact Dr J. Gronow at the DoE).

Leachate Recirculation. 1994-1996, NRA and Centre for Environmental Management funded, (contact R. Harris at Severn Trent EA).

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Investigation of Vegetation Stress Due to Landfill Leachate Migration using Airborne Thematic Mapper Data - Case Studies in South West England. 1994-1997, NERC funded post graduate research at Plymouth University (contact Dr J.S. Griffiths, A Hopper).

Instrumentation of a Permeable Liner in the Base of Stangate East Landfill. 1996-1998, DoE funded project involving Aspinwall & Co. and Greenways.

Production of a National Geographic Information System for Landfills. 1995, DoE Funded Research carried out as 14 Contracts (involves WRc, Marcus Hodges, Southern Science, Peter Dumble, Rust, La Mouchel, Robinson Fletcher, WS Atkins, Golder Associates, Babtie Robert Long).

A Study of VOCs in Landfill Sites, Gaseous Emissions and Leachate. 1993-1995, DTI/EU-Stride funded, (contact A. Braithwaite, C.C. Hills, M.R. Allen - Nottingham Trent University).

Performance of Geomembranes in Aggressive Environments. 1996, NRA R&D project, (contact GM Cachandt at E A Midlands or CP Young at WRc).

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2.6 Microbiological Contaminants

Overview

Microbiological contamination of groundwater is derived from sewage from either humans or animals. The large variety of pathogens that may be present in sewage includes pathogenic bacteria, viruses and protozoa. These contaminants can represent a potentially serious threat to public health if they are present in a water supply.

Microbiological contaminants may enter the subsurface environment via leaking sewers, leaking cesspits, septic tanks, soakaways, mineshafts used as a disposal route, landfills, or from sewage applied to the land as a fertiliser.

No current or recent research on the occurrence, transport or survival of these contaminants has been reported. However, growing awareness of the risk of contamination of groundwater sources by the protozoa Cryptosporidium in particular has resulted in the water utilities increasing their monitoring activities and carrying out risk assessments in order to guide their efforts to minimise the risk of contamination by this organism. Research has been carried out into the persistence and transport of microbiological contaminants in major British aquifers by British Geological Survey under contract to UK Water Companies. The results of this work are confidential and therefore unpublished.

Recent / Current Research Projects	Status and Contacts
• Various sampling programmes and risk evaluations of groundwater pollution by cryptosporidium.	• Ongoing internal investigations by water service companies and water companies.
• British Geological Survey Research into transport and persistence of certain pathogenic bacteria and viruses, including Cryptosporidium. Carried out for Water Companies	• Confidential research carried out by BGS Groundwater and Geotechnical Surveys Division

Key References:

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DoE/DoH, 1990. Report on the Group of Experts on Cryptosporidium in Water Supplies. Summary, Conclusions and Recommendations and Government's response. Chairman: Sir John Badenoch.

See also: Sewers, Soakaways & Septic Tanks

2.6 Microbiological Contaminants

Microbiological contamination of groundwater is derived from sewage from either humans or animals. The large variety of pathogens that may be present in sewage includes most notably pathogenic bacteria, viruses, and protozoa. If these contaminants enter water supplies they can result in a serious threat to public health.

These contaminants may enter the subsurface environment via a number of routes which includes leaking sewers, leaking cesspits, septic tanks, soakaways, mineshafts used as a disposal route, landfills, or from sewage applied to the land as a fertiliser. (With the introduction of the sludge regulations in 1989 and the impending banning of sea disposal of sludge by the end of 1998, increasing volumes of sewage sludge are being disposed of to land).

The occurrence and degree of contamination of groundwater will be largely governed by the effluent loading and the vulnerability of the groundwater to surface-derived contamination. The issue of vulnerability is dealt with in detail in section 2.13 of this report.

As a precautionary measure, groundwater used for public water supplies has traditionally been subjected to chemical treatment to ensure protection primarily from harmful bacteria which may be present at the source. More recently ozone and ultra violet (UV) treatments have been used as an alternative to protect some public groundwater supplies, whilst bacterial filters, UV, and chemical treatment have become more commonly applied to private groundwater supplies as awareness of microbiological contamination has increased. Information about the water quality of private water supplies is the domain of the local Environmental Health Department.

Previous studies into the movement of microbiological contaminants in the groundwater environment were most commonly associated with groundwater pollution incidents and to a lesser degree with investigative surveys, both of which concentrated on bacteriological and to a lesser degree on viral contamination.

Of increasing concern over the last few years has been the mounting evidence which suggests that Cyrptosporidiois (caused by the protozoa Cryptosporidium) is a water borne infection (as opposed to an infection only transferred by direct contact between humans or animals as had previously been thought). If swallowed, this microscopic single-cell parasite can cause severe diarrhoea. It is most commonly found in cattle and sheep and hence may be present in the catchment areas of many groundwater sources; and in recent months its presence has been positively detected in groundwater intended for public water supply (Water Bulletin, 672, 22 September 1995). The organism is resistant to most forms of water treatment commonly in use in the UK and thus represents a newly recognised risk to public health.

Whilst research into the life cycle and occurrence of Cryptosporidium is active, most notably at the Public Health Laboratory Service (PHLS) in N. Wales, no current research relating to the transport and survival of the organism in groundwater has been reported. The Water Service Companies and Water Companies have been and are carrying out sampling programmes and various evaluations into the risk of Cryptosporidium contamination occurring at their groundwater sources as a means of directing their actions to minimise the risk of contamination.

2.7 Non-Aqueous Phase Liquids

2.7.1 Organic Solvents

Overview

Organic solvents have been in widespread industrial use since the 1960s, when they replaced many conventional chemicals as more effective solvents in a variety of industrial processes. The physical and toxicological properties of these compounds (both NAPL and DNAPLs) causes them to be extremely insidious groundwater contaminants. As a result of their widespread use and chemical properties, they are amongst the most frequently occurring contaminants found in British aquifers. Despite this, the fate and migration of organic solvents within UK aquifers remains poorly understood and the subject has been identified as an important area of research.

Recent / Current Research Projects	Status and Contacts
• Geochemical Behaviour of Organic Pollutants	• 1995 - onwards. DN Lerner, Bradford University Laboratory studies in progress.
• Removal of Mixed Organic Pollutants from UK Aquifers	• 1995-1998 NERC PhD, C Martin, D Lerner, Bradford University).
• Natural Attenuation of Aromatic Compounds in Groundwater	• 1995-1998 EPSRC PhD, C Packwood and DN Lerner, Bradford University.
• Transport and Destruction of Organic Solvents in Groundwater	• 1995-1997, SM Grimes, Brunel University.
• Investigation and Monitoring Methods for Organic Solvent Pollution (using Biosensing Organic Xenobiotics)	• 1995 NERC and Zeneca funded research, A Meharg, Aberdeen University.
• Remediation of Organic Solvents in Groundwater	• 1995 Literature R&D project (P Waldron, EA Anglian)

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See also: Petroleum Hydrocarbons and Additives

2.7 Non-Aqueous Phase Liquids

2.7.1 Organic Solvents

Organic solvents are divided into light non-aqueous phase liquids (LNAPLs) and dense non-aqueous phase liquids (DNAPLs). LNAPLs are less dense than water and will therefore float on the surface of the water table. DNAPLs are more dense than water and will move vertically down through the saturated zone. DNAPLs may accumulate on a low permeability *boundary* and move downhill following the topography, the direction of flow may therefore be different from that of the groundwater flow.

Some of the most commonly occurring organic solvents and therefore those of the greatest concern include tetrachloroethene (PCE), trichloroethene (TCE), 1,1,1-trichloroethane (1,1,1-TCA), dichloroethane and vinyl chloride. In the past these compounds have been used in a variety of industries including the production of paint and allied products (accounting for 50% of industrial solvent use), as surface cleaning 'degreasers', in dry cleaning operations and in the production of pesticides, pharmaceuticals and other organic chemicals.

BOX 1: Selected UK Sites Contaminated by Organic Solvents.

- Eastern Counties Leather Site, Sawston, Cambridgeshire - Contamination of the Chalk aquifer by non-aqueous and dissolved phase PCE and TCE, resulted in the closure of a public supply borehole and subsequent legal battle over the liability of the polluter. Site investigations included; comparison of chemical analysis methodologies for determination of adsorbed concentrations, headspace and solvent extraction, (Stuart, 1989 BGS WD/89/52), coring and depth sampling methods to assess contaminant depth profiles, geophysical logging techniques and the use of soil gas surveys. Source containment by pumping one onsite well is currently in place as an interim remedial measure, and investigations for a permanent remedial solution are continuing.

- Harwell Laboratory, Oxfordshire - Pollution of the Chalk aquifer by a variety of organic solvents and BTEX compounds, extensive investigations included soil vapour surveys, multilevel sampling, geophysical and flow logging, followed up by a comprehensive monitoring programme. The field data were interpreted and extrapolated by the use of computer modelling techniques (Rodwell and Holton, 1995), which were subsequently used to optimise a pump-and-treat remediation system. Soil vapour extraction, air stripping and a bioremediation system have also been used on the site (Fellingham, Ateyo and Jefferies, 1993).

- Knitwear Manufacturing Company, Northumbria - Contamination of the Fell Sandstone aquifer by PCE, originating from an old soakaway lagoon on the factory site. A groundwater treatment plant has been installed at the main abstraction point and investigations for aquifer remediation continue (Kershaw and Clews, 1993).

- Chalk aquifer in the Luton / Dunstable area - A detailed groundwater quality investigation was completed on the Chalk aquifer in the Luton / Dunstable area in 1992. The programme included land use and regional groundwater surveys, invasive studies, monitoring and aquifer profiling. Widespread low level organic solvent contamination was detected, with localised hotspots of increased concentrations. The feasibility of remediating the aquifer was assessed and a 'treat at source' policy adopted (Longstaff *et al*, 1992).

2.7 Non-Aqueous Phase Liquids

2.7.1 Organic Solvents

Many of these compounds have recently (in the last 25 years) been identified as toxic and in some cases carcinogenic. Chlorinated solvents are denser than, and relatively soluble in, water, (e.g. the solubilities of TCE and PCE are 1100 mg/l and 150 mg/l respectively at 20°C). They will adsorb into solid phase in the saturated and unsaturated zones (although this effect is dependant on the organic carbon fraction which may be low in many aquifer materials). They are also relatively poorly degraded in groundwater, with the production of intermediate degradation products which are also toxic (e.g. vinyl chloride). As a consequence of the above, chlorinated solvents have a tendency to sink through groundwater (when present as free phase product - DNAPLs) continuously dissolving into groundwater. Once present in the dissolved phase they are persistent and mobile due to the low degradability and limited availability of organic carbon sorption sites. Therefore the toxicological, physical and chemical properties of organic solvents make them extremely persistent and toxic contaminants. Usage is currently being scaled down and these compounds are being replaced with more environmentally friendly products.

A literature survey of documented occurrences of UK groundwater contamination by organic solvents revealed the majority of recent research has been focused on organic solvent contamination of regional aquifers resulting from urbanisation. In particular, over the past three years there has been a number of projects based on the organic solvent contamination of the sandstone aquifer beneath Coventry. Chlorinated hydrocarbon solvent pollution was first identified here in the mid 1980s and subsequent investigations defined the origin, extent and migration of the contaminant plume (Bishop *et al*, 1993; Burston *et al*, 1993; Nazari *et al*, 1993). Professor Lerner (Bradford University) led a multinational consortium (including the geological survey of Denmark and BRGM of France) on the investigation of the solvent pollution of the Coventry aquifer between 1988 and 1991, funded by the European Community. The implications of the pollution and various suitable remedial options were identified (Lerner and Tellam, 1995; Lerner, 1995). More recently research has been completed on the fate of pollutants in urban aquifers specifically related to the Triassic sandstone beneath Birmingham (NERC grant 1990-1993, D.N. Lerner). Current research on pollution from urban sources includes a EPSRC funded project at Bradford University, 1994 to 1997, entitled 'The impact of cities on the quantity and quality of the underlying groundwater' with particular reference to the groundwater of Nottingham. Organic solvent pollution has been identified at a great many other sites within the UK, of these some of the most well known are listed in Box. 1.

A recent NRA review of the principal controls on migration of halogenated solvents (NRA Note 46 and 47) summarises what is currently known about the behaviour of organic solvents in the subsurface. The major hydrogeological processes relevant to organic solvent migration are listed in Box 2. However our understanding of the fate and migration of organic solvents in UK aquifers is still limited. This subject is recognised as an important research topic and a number of laboratory based projects have recently started. These include:

- The geochemical behaviour of organic pollutants, involving laboratory studies on sorption, dissolution, degradation and diffusional behaviour of a range of organic pollutants (chlorinated solvents, BTEX compounds and triazine pesticides), is underway at Bradford University (D Lerner, M Barrett and S Needham).
- Removal of mixed organic pollutants from UK aquifers, a NERC PhD studentship (1995 to 1998) mainly involving laboratory studies. Bradford University (DN Lerner, C Martin)

2.7 Non-Aqueous Phase Liquids

2.7.1 Organic Solvents

- Natural attenuation of aromatic compounds in groundwater, EPSRC PhD studentship (1995 to 1998) field and laboratory studies. Bradford University (DN Lerner, C Packwood)

The occurrence of chlorinated solvents in groundwater is difficult to predict due to the physical and chemical characteristics of the pollutants. Previous experience (mostly in the US) has highlighted the importance of good site investigation/characterisation practices. A large amount of literature is available describing site tests, investigation practices and analytical methods (Bishop *et al* 1990, Eastwood *et al* 1991, Marrin and Kerfoot 1988, Stuart 1991). However, the only current UK research on this subject, known to the authors at the time of writing, are investigations into the use of biosensing and xenobiotics for site investigation and monitoring purposes (Combined NERC / Zeneca funded PhD studentship at the University of Aberdeen, contact: A Meharg).

BOX 2 : Major Hydrogeological Processes *Relevant* to Organic Solvent Migration (identified by FWR, 1995).

Saturated Flow	Flow direction and flow rates have a strong influence on contaminant pathways.
Fracture Flow	Preferential flow of water, dissolved and separate phase contaminants can be extremely fast and greatly affect the migration of a contaminant plume.
Multiphase Flow	Modelling multiphase flow is difficult.
Gas Exchange	Transport of organic vapours can significantly influence the spread of contamination.

Remediation of groundwater impacted by organic solvents is covered in more detail under Section 2.11 of this document. A few important projects specific to organic solvent contaminants are mentioned here. A national guidance document on the implementation of remedial action at sites contaminated by organic solvents has recently been completed by the NRA. The document is a result of an extensive literature review, presenting recommended site characterisation and remedial action plans for sites contaminated by organic solvents and in particular free phase DNAPL.

Specific future research requirements on organic solvent pollution of groundwater are identified as: defining techniques and strategies for delimiting, for source control and for containment of NAPL spills, and definition of optimal methods for remediation under different hydrogeological and contaminant conditions. In terms of applied research, further laboratory studies are needed to determine the fundamental processes of contaminant migration and verification at a field scale (FWR, 1995).

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2.7 Non-Aqueous Phase Liquids

2.7.1 Organic Solvents

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2.7 Non-Aqueous Phase Liquids

2.7.1 Organic Solvents

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2.7 Non-Aqueous Phase Liquids

2.7.2 Petroleum Hydrocarbons and Additives

Overview

The widespread use of petroleum products as fuels, lubricants, solvents, etc., has led to high incidence of groundwater contamination by hydrocarbons. Long standing recognition of the pollution threat from petroleum hydrocarbons and additives has prompted previous research into groundwater contamination by these products. This research has produced well documented understanding of the biochemistry and contaminant migration characteristics of petroleum hydrocarbons. Recently, research has focused on practical site characterisation and methods of remediation. As a consequence, a number of key guidance documents has been produced.

Recent/current Research projects	Status and Contacts
• Guidance Manual on Underground Fuel Storage Installations in Sensitive Groundwater Situations	• 1996, EA R&D (Midlands Region). Project no. A08(95)5.
• Guidance Document for a Uniform Approach to Remediation Decisions Based on Risk Reduction.	• 1995 - onwards, CONCAWE research project. Contact P Bartholomae (BP Oil Co., Brussels).
• Modelling of Contaminant Fate of Hydrocarbons in Ground and Groundwater.	• 1996, CIRIA funded, Contact I Viney at Celtic Technologies.
• Natural Attenuation of Aromatic Compounds in Groundwater	• 1995 - 1998, EPSRC funded PhD studentship; Contact C Packwood & Prof D Lerner at Bradford University.
• Characterisation of Petroleum Wastes as NAPLs in the Vadose Zone	• 1993 - 1996; (Uni of Edinburgh), Contact Dr S Pollard at Aspinwall & Co..
• Enhanced Degradation of Diesel in an Aqueous System by Immobilised *Pseudomonas fluorescens.*	• 1993 - 1996, BBSRC funded PhD studentship. Contact Dr G Bradley at Plymouth University.
• Organic Solvent and Hydrocarbon Removal by Membranes.	• 1993 - 1996, 2 EPSRC funded projects; Contact Prof K Scott at Newcastle University.
• Microbial Ecology of Hydrocarbon-Degrading Bacteria during Oil Spill; Bioremediation using Molecular Biological Methods.	• 1993 - 1996, US EPA/UK AEA funded. Contact Dr I Head at University of Newcastle, and R Swanell at AEA Technology.
• Project to define the threat posed by MTBE and its usefulness as a pollution indicator.	• 1996 EA R&D Project No. A08(95)04C

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- Institute of Petroleum (1992). Code of Practice for the Investigation and Mitigation of Possible Petroleum Based Land Contamination.
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See also: Organic solvents, Contaminated Land

2.7 Non-Aqueous Phase Liquids

2.7.2 Petroleum Hydrocarbons and Additives

Hydrocarbons are used as fuels (petrol, diesel, kerosene, fuel oil), solvents and chemical feedstocks in the textile, pharmaceutical and plastic industries; they represent one of the most widely used groups of chemicals in the industrial world. This widespread usage has led to numerous major and minor groundwater pollution incidences worldwide. In the UK, the extent of petroleum hydrocarbon pollution is not well defined. However the number of independent site investigations and remedial implementations indicates petroleum hydrocarbon point source contamination incidences are extremely common.

The hydrocarbon content of petroleum products primarily consists of alkanes, (both n-alkanes (e.g. octane) and branched alkanes (e.g. pristane)), and aromatics (e.g. BTEX compounds benzene, toluene, ethlybenzene and xylenes), including polynuclear aromatic hydrocarbons (PAHs), such as naphthalene and fluoranthene. Non hydrocarbon components are also present, these include naturally derived compounds (e.g. aliphatic and aromatic carboxylic acids) and additive complexes. Some of the most commonly occurring additives are tetraethyl lead and methyl-tertiary-butyl ether (MTBE).

Current and recent research on petroleum hydrocarbons as groundwater contaminants is extensive. This reflects the recognition of the pollution threat posed by these compounds. In recent years the focus of research (often oil company funded) has moved from laboratory based biochemical investigations, to practical investigations into the behaviour of petroleum related contaminants in aquifers and the potential for remediation. The majority of UK work identified in this study is based on site investigation and remediation studies. Specific compounds and hydrocarbon groups from petroleum products, such as benzene and MTBE, have been recognised as serious groundwater pollutants, and consequently have been singled out as important research topics.

Numerous guidance documents have been published advising on site characterisation and risk assessment approaches for hydrocarbon contaminated sites, these are listed as key references on the previous page. CONCAWE (The Oil Companies International Study Group for Conservation of Clean Air and Water - Europe) issued the guidance document 'Protection of Groundwater from Oil Pollution' in 1979. More recently, 1992, the Institute of Petroleum published a code of practice for the 'Investigation and Mitigation of Possible Petroleum Based Land Contamination'. The document provides a comprehensive review of all stages involved in the implementation of remedial projects. Guidance on the assessment of petroleum releases, and evaluation of remedial technologies is available from the US Environmental Protection Agency and American Petroleum Institute (USEPA, 1994; API 1995).

Current UK research includes the development of a guidance manual on underground storage tank installations in sensitive groundwater situations, to reduce risk of contamination (EA R&D project A08(95)5), and the development of guideline documents for a uniform approach to remediation decisions based on risk reduction (current CONCAWE project).

The biodegradation of hydrocarbon contaminants has long been an important area of research, it is generally accepted that the application of bioremediation to petroleum hydrocarbons is the niche in which the technology is most completely developed. Recent research abroad (USA, Germany and the Netherlands) has furthered the use of innovative in-situ technologies for remediation of petroleum hydrocarbon contaminated groundwater (Hinchee, Kittel and Reisinger, 1995).

The increasingly frequent occurrence of the additive MTBE in UK groundwater, has stimulated current research into the occurrence and behaviour of the compound. The EA R&D project A08(95)04C aims to improve the understanding of the threat posed by MTBE and its usefulness as a pollution indicator, (work started in January 1996 and is due for completion by July 1996). It has been suggested that MTBE has a cosolvency effect, which increases the solubility of BTEX and other petroleum hydrocarbons, (Kramer and Hayes, 1987). However recent studies conducted by the American Petroleum Institute (API) have not confirmed this phenomena, (API 1991a). Other effects including causation of reduced adsorption potentials have also been suggested. The API has produced a guidance document describing cost-effective alternative technologies for reducing MTBE concentrations in groundwater, (API, 1991b).

PAHs are the most recalcitrant components of petroleum products. Groundwater contamination by PAHs is often sourced from old gas work sites, domestic coal burning, vehicle emissions, landfills and sewage sludge. PAHs are less water-soluble than the lighter petroleum fractions and tend to adsorb to soil particles, thus restricting mobility. However, their presence in soils and groundwaters is of particular concern owing to the toxicity and strong potential to bioaccumulate, (Wild *et al*, 1995). In a recent study including a source inventory and budget, the total amount of PAH contaminants present in the UK environment was estimated at 53,000 tonnes, (Wild & Jones, 1995). These are, at present, mostly contained in soil. However PAH soil contamination is estimated to be increasing by a rate of 1210 tonnes per year, posing a potential threat to groundwater.

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2.7 Non-Aqueous Phase Liquids

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2.7 Non-Aqueous Phase Liquids

2.7.3 Future Research Topics

The objectives and requirements for future research on NAPL contamination in UK groundwater, have been assessed by the FWR, 1995, see Box 1.

BOX 1: Research Objectives and Requirements for the Groundwater Issue of Non-Aqueous Phase Liquids (NAPLs), identified by the FWR, 1995.

Research Objectives

- Improvements in the understanding of the fate of NAPLs in groundwater and definition of the extent of present contamination of UK groundwaters, enabling risk assessment, quality prediction and the design of mitigating actions.

Operational Research Requirement

- Definition of site characterisation techniques, and remedial methods under different hydrogeological and contaminant conditions.

Applied Research Requirements

- Definition of fundamental processes of DNAPL migration
- Assessment of importance of preferential flow
- Practical use of multiphase flow models
- Development of rapid site characterisation techniques
- Development of methods for estimating residual saturation
- Identification of the interaction and passage of NAPLs through aquifers

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2.8 Pesticides

Overview

Pesticides include insecticides, fungicides and herbicides, all of which are widely used by industry, public authorities and in agriculture. As a result of the wide range of pesticides and the complexity of their transport in the soil and subsurface environment, the detailed mechanisms of pesticide attenuation and degradation are not fully understood. Increasing awareness of the pollution threat presented by these chemicals has in recent years resulted in pressures to reduce their usage or switch to less toxic or less persistent pesticides. It is not yet clear whether these measures alone will be sufficient in bringing about a significant reduction in groundwater contamination from these substances.

Recent / Current Research Projects	Status and Contacts
• Pesticides in UK Groundwaters - Phase II	• 1996, EA R&D Anglian region (contact: D Tester).
• Assessment of Movement of Individual Pesticides in Groundwater.	• 1994-1997, Agro-Chem funding, (contact AD Carter and P Fogg at SSLRC).
• Further Analysis on Presence of Residual, and Impact of, Plant Protection Products in the EU.	• 1995-1996, EU and Dutch Govt funding, (contact A Carter at SSLRC).
• CATCHIS Computer Modelling of Pesticides in Soil	• 1994-1998, Severn Trent Water plc. funding (contact JM Hollis at SSLRC).
• Herbicide Losses from Hard Surfaces and the Effect on Groundwater and Surface Water Quality.	• 1995-1997, PSD, EA, Agro-Chem, (contact A Carter at SSLRC).
• Pesticides and Transformation Products in Aquifers.	• 1996, EC funding. (Contact B. Hegarty and J. Turrell at WRc).
• Bioremediation of Pesticide Contaminated Water.	• 1994 to 1997. Research Technology Biosciences, Anglian Water, FWR and BBSRC funding, (contact Prof R. Burns at Kent University).
• Sorption Studies of Pyrethroid Pesticides to Soils and other Particles.	• 1990-1995. Zeneca Plc and Agrochemicals funding, (contact Prof. S. Rowland at Plymouth University).

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Clark, L., *et al.* (1992). Pesticides in Major Aquifers. NRA R&D Note 72, 36p.

Needham, S.N., and Lerner, D.N. (1995). The Behaviour of Atrazine and Simazine within the Chalk Aquifer. NRA R&D Report 01/538, 38p.

Foster, S.D., Chilton, P.J. & Stuart, M.E. (1991). Mechanisms of groundwater pollution by pesticides. J. Institution Water & Environmental Management ,5(2), p186-193

See also:

2.8 Pesticides

Whilst groundwaters are generally considered to be less vulnerable than surface waters to direct contamination by pesticides evidence indicates that residual pesticides are nevertheless significantly impacting groundwaters in the UK. Some research suggests that the problem is rapidly assuming the same scale as nitrate contamination. Indeed the two are often found in association. Despite this, the amount of research on the occurrence and transport of pesticides in UK is considerably less than that carried out on nitrates in groundwater.

Pesticides are both toxic and persistent in the environment and can represent a potentially significant health hazard; especially given their capacity for bioaccumulation in the food chain. The EC Drinking Water Directive set a maximum admissible concentration in drinking water for individual pesticides at a very low level (0.1μg/l). In relation to the analytical capabilities of the time, this was effectively a surrogate zero. Close monitoring of this standard over recent years, together with improved analytical techniques, (lowering detection limits for the various laboratory methods), has resulted in identification of an increasing number of pesticides in groundwater. Evidence of the widespread occurrence of pesticides in groundwater can be found via reference to site specific studies and nationwide surveys which reveal that the EC Drinking Water maximum admissible concentration has been exceeded in some British water supply boreholes (Lees & McVeigh, 1988; DoE 1992; Clark *et al* 1992). However it should be stressed that both scientific investigation and monitoring of pesticides present significant difficulties. It is not practical for a water utility or regulatory authority to monitor for all of the large number of pesticides in regular use in the UK (Chilton and Lawrence, 1994). Selective analysis has to be employed to target the pesticides which pose the highest health risk, those which are widely used, mobile, and persistent; whilst the sampling needs to be focused on the

BOX 1 : Major Hydrogeological Processes Relevant to Pesticides (identified by FWR,1995)

Soil Processes	Sorption onto soil particles and chemical and microbiological degradation are important attenuation mechanisms
Unsaturated Flow	This zone provides an important delay mechanism between a contaminant at surface and the aquifer. Solute movement within and attenuation properties of this zone are important controls on migration
Saturated Flow	Flow direction and flow rates have a strong influence on migration pathways
Fracture Flow	Preferential flow of groundwater and contaminants, potentially with little attenuation, can affect the migration and impact of a contaminant plume
Reactive Transport	Includes reaction within and sorption onto the aquifer matrix and thereby the fate of contaminants once in the groundwater
Microbiological Process	Are responsible for the breakdown and attenuation of contaminants in the soil, unsaturated and saturated zones.

most vulnerable aquifers or sources. This approach is embodied in the NRA R&D Report No. 17 (NRA, 1995), which investigates the fate and transport of selected priority pesticides in both surface and groundwater. The project relates measured pesticide concentrations to their physicochemical properties and pattern of use, developing predictive models for pesticide transport physico and fate.

The pesticides most commonly encountered in groundwater at significant concentrations in a study carried out by NRA/WRc in 1992 and 1993, (NRA, 1995) were:

- Bentazone -/15
- Atrazine 9/11
- Trietazine 3/5
- Diuron -/5
- Terbutryn 4/2
- Pentachlorophenol -/4
- 2,3,6 TBA 0.8/4
- Linuron 0.7/3
- Clopyralid -/3
- Ethofumesafe -/3
- Isoproturon 2/3
- Chlorotoluron 0.5/2
- Simazine 0.7/2
- Mecoprop 1/1

Some of the pesticides most frequently detected in groundwater are herbicides (e.g. atrazine, simazine, mecoprop and isoproturon). Carbamates, chloropropanes and triazines have all been identified in concentrations exceeding 1μg/l in shallow aquifers in both Europe (including the UK) and the USA. The triazines are of non-agricultural origin and tend to be extremely persistent. Usage of triazine has recently been replaced by diuron, however the legacy of past triazine usage remains and diuron is now also being identified in groundwater. The use of non-persistent herbicides such as glyphosphate is now being encouraged in preference to other herbicides. Glyphosphate is a relatively expensive alternative and therefore the widescale use of diuron and other persistent herbicides will continue in the absence of legislative pressures.

Despite the recent research there is relatively limited knowledge available regarding the fate of pesticides in both the soil and groundwater environment. This is largely due to the complexity of pesticide transport in the soil and subsurface environment, and the fact that the behaviour of a particular compound may vary significantly depending upon conditions in the soil and aquifer (Chiltern and Lawrence, 1994). A list of the major hydrogeological processes relating to pesticides is presented in Box 1. The fate and transport of pesticides above the water table is controlled in part by sorption onto, and leaching from, the soil, volatilisation and loss from both the soil and plants, and degradation by microbes in the unsaturated zone. Pesticides are significantly more mobile and persistent on reaching the saturated zone due to a reduction in the amount of organic matter and lower microbiological activity.

The most vulnerable aquifers are those with overlying thin permeable soils (where leaching and movement is enhanced), a shallow water table and low porosities where dilution is minimal (Chilton and Lawrence, 1994). The importance of the unsaturated zone for controlling the occurrence of pesticides in groundwater has been recognised (Clark and Gomme, 1992), recent research in this area is summarised in Box 2.

2.8 Pesticides

The importance of research in this field is now well recognised, with a range of current research projects funded by EC, EA, Water Companies and industrial agro-chemical firms. It is expected that current research will improve the understanding of pesticide transport and fate in groundwater together with the present extent of contamination. This should allow improvements to risk assessments, methods of predicting groundwater quality, and the design of remedial actions to ensure compliance with water quality standards. To date, experience of remediation of pesticide contaminated groundwater in the UK is limited but may benefit from current research into the bioremediation of pesticide contaminated water to evaluate the application of bioremediation as a water treatment technology (contact: Prof. R.G Burns, Kent University).

BOX 2: Recent Research in Pesticide Movement through the Unsaturated Zone

- **Beck *et al.* (1995)**, investigated the spatial and temporal variability of water flow paths and their influence on the transport of atrazine and isoproturon through a clay soil. They considered that movement was dominated by flow along cracks and voids.

- **McGhee and Burns (1995)**, investigated the biodegradation of 2,4-D and MCPA in soils. These compounds are considered to be persistent because either the physical or chemical environment was unsuitable for degradation, i.e. the pH was inappropriate, only low levels of nutrients were available, the soil was compacted and anaerobic, organics had been adsorbed onto the soils or competent bacteria were absent. Modification to the pH, nutrients and aeration could be undertaken to accelerate the degradation of MCPA.

- **Zhou *et al.* (1995)**, undertook a study on the behaviour of cypermethrin in soils, identifying that the pesticide was most strongly adsorbed onto organic rich particles. They have also recently completed a study on the behaviour of pyrethroids in soils at Plymouth University.

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2.9 Radioactive Waste Disposal

Overview
Extensive research has been carried out and funded by the nuclear industry investigating options for radioactive waste disposal. Low-level waste (LLW) is generally derived from medical and research facilities, the vast majority of which is disposed to landfill. UK Nirex plan to build an intermediate-level waste (ILW) repository at Sellafield, and high-level waste (HLW) will be stored at surface until it becomes ILW. All radioactive waste poses a potential threat to groundwater and creates a long term problem due to the slow rate of radioactive decay. Repository storage in particular has prompted hydrogeological investigations and research into the transport of radionuclides.

Recent / Current Research Projects	Status and Contacts
• Sellafield Geological and Hydrogeological Investigations to Support Determination of the Suitability of the Site to Host a Radioactive Waste Repository.	• 1990-2000, Funded by NIREX share holders (contact A Littleboy at NIREX).
• Radioactive Waste Disposal Cation Adsorption on to Specific Sites of Clay Minerals in Particular Caesium and Strontium.	• 1993-1996. Funded by British Nuclear Fuels. (contact JV Holder, RW McCabe, BN Osborne) University of Central Lancaster.

Key References:

Berry, J.A., Bond, K.A., Cowper, M.M., Green, A., Linklater, C.M. (1994). Factors Influencing the Diffusion of Uranium, Plutonium and Radium through Sherwood Sandstone from Sellafield, Cumbria. Radiochimica Acta, **66-7**, p447-452.

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Olsson, O., and Gale, J.E. (1995). Site Assessment and Characterisation for High Level Nuclear Waste Disposal: Results from the Strippa Project, Sweden. Quarterly Journal of Engineering Geology, **28**, p517-530.

Savage, D., and Rochelle, C.A. (1993). Modelling Reactions between Cement Pore Fluids and Rock - Implications for Porosity Change. Journal of Contaminant Hydrology, **13**, No.1-4, p365-378.

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Forthcoming QJEG Supplement: The Hydrogeology of Sellafield.

See also: Radionuclides

2.9 Radioactive Waste Disposal

Identification of different options for radioactive waste disposal has prompted a large amount of research into the fate and transport of radionuclides under different hydrogeological conditions. In particular there have been extensive hydrogeological and contaminant transport studies of leakage of radioactivity at Drigg, Cumbrian and other potential ILW sites in the UK, as it is recognised that the understanding of past flows is the key to predicting future flow.

Extensive hydrogeological and geological research is ongoing at Sellafield in a research programme to determine the suitability of the site to host a radioactive waste repository. The programme includes a large variety of projects involving field investigations, laboratory experiments and modelling studies and is set to continue into the early 21st century. A summary of the work to date is given in Nirex 1995: (A Preliminary Analysis of the Groundwater Pathway for a Deep Repository at Sellafield, Report no. F/95/012), and Nirex, 1993, (Nirex deep waste repository project - Scientific Update 1993, Report no 525), and forthcoming Quarterly Journal of Engineering Geology Supplement (The Hydrogeology of Sellafield).

The main focus of recent literature is the transport of radionuclides in groundwater. Summaries of recent literature are presented in Box 1.

BOX 1: Review of Current Literature on Radioactive Waste Disposal

Williams (1992) discusses the physical and mathematical problems associated with radioactive waste disposal with emphasis on modelling radionuclide transport through spatially random media such as fissured and porous rock.

A study by MacKenzie *et al* (1992) looked at processes occurring at redox fronts in a natural uranium deposit and identified a potentially important retardation mechanism which may occur in a repository-related redox front.

Savage and Rochelle (1993) suggest that radionuclide retardation will be enhanced by the growth of zeolites and calcium silicate hydrates as groundwater equilibrates with cement from the repository, and changes the chemical, mineralogical and physical properties of the geosphere in advance of the migration of radionuclides.

Experiments on cation (specifically caesium and strontium) sorption onto clay minerals have been reported by Osborne *et al.* (1995).

Williams and Higgo (1994) and Berry *et al* (1994) look at the processes which control contaminant transport in aquifers. Williams and Higgo integrated laboratory and field approaches to study the role of colloids in transporting radionuclides in intergranular material.

Berry *et al* (1994) carried out laboratory experiments using geological samples from the Sherwood Sandstone group, Sellafield, Cumbria, to study the factors influencing the diffusion and sorption of uranium, plutonium, and radium.

Small quantities of LLW are disposed of to landfill, and these wastes are generally derived from medical or research facilities. The disposal of these wastes is controlled by statute and are generally considered to represent little threat to the environment.

2.9 Radioactive Waste Disposal

Disposal of any radioactive waste requires an authorisation under Section 13 of the Radioactive Substances Act, 1993. Disposal to landfill requires authorisation under the waste management licensing provisions of the Environmental Protection Act, 1990. The objectives of these provisions are to ensure that waste management facilities do not cause pollution of the environment, do not cause harm to human health, and do not become seriously detrimental to the amenities of the locality. Regulation 15 of the Waste Management Regulations, 1994 (SI No.1056) transfers into British law certain requirements of the EC Groundwater Directive (80/68/EEC), the general purpose of which is to protect groundwater from pollution from certain listed substances including substances which possess carcinogenic, mutagenic and teratogenic properties in an aquatic environment.

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Williams, M.M.R. (1992). Stochastic Problems in the Transport of Radioactive Nuclides in Fractured Rock. Nuclear Science and Engineering, **112**, No.3, p215-230.

Williams, G.M., and Higgo, J.J.W. (1994). In-situ and Laboratory Investigation into Contaminant Migration. Journal of Hydrology, **159**, No.1-4, p1-25.

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2.10 Radionuclides

Overview

Radon, radium, and uranium are naturally occurring radionuclides, found in certain rock types such as granite. They move as dissolved species in groundwater or as a gas. Naturally occurring radionuclides are not generally a concern in UK groundwater. However radon occurs mainly as a gas, and high concentrations of radon gas have been measured in buildings in certain areas of the UK, which may pose a significant health hazard. Research on radionuclide presence and migration in groundwater is mainly related to the protection of groundwater from radioactive waste, generated from the nuclear power industry (this is covered under section 2.9).

Recent / Current Research Projects	Status and Contacts
• No current research on naturally occurring radionuclide pollution of groundwater identified.	

Key References:

Ball, T.K., Cameron, D.G., Colman, T.B., and Roberts, P.D. (1991). Behaviour of Radon in the Geological Environment - A Review. Quarterly Journal of Engineering Geology, **24**, No.2, p169-182.

See also: Radioactive Waste Disposal

2.10 Radionuclides

Present concentrations of radionuclides in groundwater are not significant and since these substances are naturally occurring there is no reason to believe the situation is deteriorating. Although radon, radium and uranium are suspected carcinogens, direct intake in drinking water is not believed to be a problem (most studies on the health effects of these substance have been carried out in the US). Thus groundwater pollution by naturally occurring radionuclides is very minor and not perceived as a problem in the UK.

No specific projects relating to this subject were identified in the literature search, however there is a great deal of related research on the fate and transport of radioactive waste substances, this is described in section 2.9.

Previous studies on radionuclides in groundwater include using radionuclide isotopes to study the timescales and processes involved in rock/water interactions in the Lower Mersey basin (Ivanovich *et al.* 1992b), and in rock/brine interactions at depth in crystalline rocks (Ivanovich *et al* 1992a).

Identification and occurrence of radon in the environment has been a more active area of research. An overview of the behaviour of radon in the geological environment, including a summary of procedures for the analysis of radon in water is presented in Ball *et al*, 1991. Assessment of radon concentrations in surface waters and techniques for identifying high-risk radon areas have been presented by Heath, 1991. Finally measurement of radon in Chalk groundwaters has been used to estimate fracture apertures in the saturated zone (Younger and Elliot 1995).

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2.11 Remediation

Overview

Remediation of contaminated groundwater covers treatment and contaminant removal technologies as well as pollution containment. Various groundwater remedial actions have been implemented in this country. However the effectiveness in UK aquifers of the variety of techniques available is not fully understood. At present there is very limited documentation of remediation projects in this country that is readily accessible. The most extensive experience and documentary evidence is in the USA, where most groundwater remediation technologies have been pioneered, and research and experimentation into new and existing technologies is actively undertaken.

Recent / Current Research Projects	Status and Contacts
• Core Program Remedial Treatment of Contaminated Land Phase III.	• On-going (1995) phases I and II complete, CIRIA.
• Review of Research on Process Technologies for Remediation of Contaminated Land.	• 1995 completion, prepared by Nottingham Trent University, DoE funding (proj. Ref. 45).
• Guidance on the degree of soils clean-up needed to protect water resources.	• EA R&D A08(95)2a, Project No. 714, Dames & Moore, Contact: Bob Harris (EA Midlands).
• Evaluation of Remedial Actions for Groundwater Pollution.	• 2/95 to 8/95, EA, P Waldron & Geraghty & Miller International, ongoing.
• Guidance for Evaluating the Performance of Remedial Measures for Contaminated Land.	• 1995 completion, prepared by CH2M Hill, DoE funding (Proj. ref. 30).
• Derivation of groundwater quality clean-up standards	• EA R&D A08(95)2b, Project No. 657 WRc, Contact: Bob Harris (EA Midlands)
• Combined Treatment and Containment Systems: Review of Approaches and Identification of Low Cost Combinations.	• 1995 completion, prepared by Golder Associates, DoE funding (Proj. Ref. 56).

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Holden, J, Muldoon, D, and White, C,. (1995 in press). Core Programme Funders Report. Remedial Treatment of Contaminated Land; Hydraulic Control and Pump and Treat.

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See also: Contaminated Land

2.11 Remediation

Incidences of reported groundwater pollution in the UK are becoming increasingly frequent. A wide range of organic and inorganic contaminants has been detected, mainly as a result of contamination from active and closed industrial facilities. It is anticipated that the legacy of past anthropogenic activities will be increasingly seen in groundwater, as today's contaminated land becomes tomorrow's groundwater pollution problem. Remediation is therefore rapidly becoming a necessary option, to restore or conserve groundwater quality and remove or contain contamination sources.

There is a large variety of remedial technologies available that have potential for groundwater remediation, most of these were developed abroad (USA, the Netherlands and Germany). The effectiveness of these techniques as applied to the UK environment has not been clearly defined.

In the past most remediation technologies have been developed aiming for rapid treatment, making intensive use of energy and resources. Interest in lower input technologies has recently grown in the UK. These 'extensive' technologies, take longer to become effective, but have lower costs and require less input. Bardos and van Veen, 1996 review a number of proposed extensive technologies in terms of 'environmental merit'. This is an assessment of technologies in relation to a number of environmental themes (e.g. global warming, ozone depletion potential, human toxicity). A recent study carried out by the Dutch environmental consultancy, TAUW, concluded the dominant themes affecting environmental merit for remediation of contaminated sediments were: energy consumption, waste production and water toxicity. Box 1 presents a summary of current and emerging extensive technologies.

The extent of remediation required is dictated by the target concentrations set. There are two principal categories of remedial targets, site specific corrective action target levels and non-site specific risk based target levels. In the UK, target concentrations tend to be site specific, due to the absence of published guideline concentrations. A new EA R&D project, started in January 1996, aims to develop and provide guidance for using site specific risk based target values for the remediation of groundwater. The development of generic guideline values for contaminants in groundwater has not been attempted in the UK and the Dutch intervention and target values are often referred to instead. Generic target concentrations in soils are being developed, in work funded by the DoE under the contaminated land research program, see below. The report is due to be published in the spring of 1996.

The development of general guidance documents for the implementation of remedial actions is an area of active research. Two extensive current research programmes run by the DoE and CIRIA are described below:

The Construction Industry Research and Information Association (CIRIA) is at present managing extensive research into the remedial treatment of contaminated land. The project is in three phases. Phase I is complete and a 12 vol. report, documenting guidance for decommissioning, site characterisation, remedial selection, implementation and closure, has been published (CIRIA reports SP101 to SP 112). Phase II is also complete, and a set of state of the art reviews on remedial technologies has been produced. Phase III is in progress and includes reviews of a number of case studies, comparing remedial technologies in use in the EC.

2.11 Remediation

BOX 1: Current and Emerging 'Extensive' Treatment Technologies	
Bioventing	Bioventing is an adaptation of soil vapour extraction technology designed to maximise biodegradation rates, while minimising volatilisation and therefore minimising vapour treatment. Bioventing stimulates biodegradation by enhanced supply of oxygen to micro-organisms in the soil. This method of supply is far more effective than previously used pump-&-treat circulation methods. Air sparging may offer similar possibilities for enhanced biodegradation in the saturated zone. The possibility of introducing heat, moisture and nutrients to the subsurface in the vapour phase through these systems has also been explored.
Use of plants for remediation	Investigations into the use of plants for heavy metal removal, organic contaminant removal and stimulation of biodegradation have provided promising results. As far as technical implementation is concerned these approaches are only emerging concepts. However the use of plants scores relatively highly in environmental merit and further research into these technologies is recommended.
Electro-remediation	Electro-remediation is the application of an electrical field to stimulate migration of ions or polar compounds. This force can be applied to move contaminants or micro-organisms to *in-situ treatment zones*, to contain them or move them back and forth across *treatment zones*.
Hydraulic Fracturing	Hydraulic fracturing is a means of introducing horizontal zones of enhanced permeability into the ground. The technology may be used to assist both venting and pump-&-treat based systems.
In-situ Treatment Zones	A treatment zone is a designated treatment region into which controlled movement of contaminants is achieved. In-situ treatment zones may be emplaced across aquifers, through chemical and biological seeding within permeable treatment walls. The controlled movement of contaminants can be achieved through natural or managed groundwater flow (funnel and gate technologies) or the use of electro-osmosis.
Active Containment	Active containment refers to the integration of treatment with containment. This is an emerging approach under development in a number of countries. A review of approaches has been commissioned by the UK Department of Environment. Current research and development activities include the concept of bio-screens (TNO in the Netherlands), biologically enhanced barriers (USA and UK, Nottingham Trent University) and biological clogging as a repair mechanism (USA and Australia).
Altering availability and/or toxicity	A number of biological and non-biological processes may reduce availability and/or toxicity of contaminants, including: biological transformation, sorption/immobilisation and chemical stabilisation. It has also been proposed that revegetation of contaminated sites may have beneficial effects in limiting contaminant migration.
Enhancing natural processes of decay and attenuation	Enhancing naturally occurring decay and attenuation processes is already used in a number of applications including: municipal and co-disposal landfill technologies; the use of wetlands for treating acidification; the use of reed beds for treating industrial and municipal wastewaters; and the use of low level fertiliser to stimulate biodegradation of oil spills on beaches. In the past most remediation development has been based on empirical research directed towards relatively rapid solutions. However the effectiveness of intrinsic bioremediation is likely to be greater over longer time scales and requires lower input conditions. To achieve these ends a greater fundamental understanding of the processes involved is required.

2.11 Remediation

The Department of the Environment (DoE), contaminated land division, has an extensive research program on the remediation of contaminated land. Current projects include work on risk assessment methodologies, evaluation of remedial treatments, quality assurance and management procedures. For a complete project listing the reader is referred to the Contaminated Land Research Program publication available from the DoE.

The evaluation and feasibility of remedial technologies have been the subject of extensive research in the US, and although work is underway in the UK it does not approach the scale of North American activity. A list of current UK projects concerned with specific sites/contaminants is provided in Box 2. Projects include methods of removing a variety of contaminants from groundwater using in-situ remediation treatments and evaluation of intrinsic (i.e. natural) bioremediation and other attenuation processes. The majority of evidence for the effectiveness of the various remedial techniques in the UK is largely based on a limited number

BOX 2: Current UK Research Projects on Specific Groundwater Remediation Technologies and Case Studies

- Processes underlying the remediation of creosote contaminated groundwater in fractured sandstone; 1995 to 1997 EU Environment program, D.N. Lerner (Bradford University), C. Mouvet and L Almari (Technical University of Denmark).
- Removal of mixed organic pollutants from UK aquifers; 1995 to 1998, NERC Ph.D. studentship, D.N. Lerner, C. Martin (University Bradford).
- Bioremediation of pesticide contaminated water; 1994 to 1997 FWR and BBSRC, Research Technology Biosciences (Kent University, contact Prof RG Burns), Anglian Water Environmental Sensors Ltd.
- Enhanced bacterial degradation of hydrocarbons using immobilised systems; BBSRC, final year. University of Plymouth, contact Dr G Bradley.
- Definition and remediation of both ground and surface water pollution at Baffins Pond Portsmouth; 1993 to 1996 Portsmouth City Council, NRG Walton, D.P. Giles, S. Meyer (University of Portsmouth).
- Heavy metal removal by electrodeposition and liquid membranes, organic solvent and hydrocarbon removal; 1993 to 1996, EPSRC, Prof K Scott (Newcastle University).
- Organic solvent, hydrocarbon and inorganic chemical removal by membranes; 1992 to 1995 EPSRC, Prof K Scott (Newcastle University).
- Natural attenuation of aromatic compounds in groundwater; 1995 to 1998. EPSRC Ph.D., C. Packwood and D.N. Lerner, Bradford University.
- Removal of toxic metals from water and their recovery as metals by biosorption, elution and electrolysis; 1996 to 1999 EC funding, I.C. Hancock, L. Evison (Newcastle University) and colleagues in Portugal and Greece.

of case studies. These have generally been undertaken by environmental consultants on industry's behalf and are therefore not published.

Some key documents produced by the U.S. Environmental Protection Agency (EPA) report on the general applicability and feasibility of a wide range of remedial technologies for contaminated groundwater and soils. The Remediation Technologies Screening Matrix and Reference Guide, includes details of currently understood contaminant properties and behaviour, the treatments available and their applicability, limitations, data requirements and performance costs. Resource Guides, documenting information on resources for bioremediation, soil vapour extraction, groundwater treatment technologies and physical/chemical treatment technologies are also available.

It is recognised that further research is required in the UK to:

1. Analyse the physical and chemical processes involved in contaminant remediation, including an understanding of their transport properties.
2. Develop and improve remediation techniques, especially for enhanced bioremediation.
3. Improve the monitoring and modelling of remedial activities so that their effectiveness can be evaluated.
4. Develop risk assessment and decision support systems for designing cost effective remedial strategies, including the selection of appropriate generic and site specific remedial target concentrations.

This will enable the development of monitoring technologies, allowing the identification of a series of cost effective remedial options applicable under differing hydrogeological conditions and for a variety of contamination incidents (FWR, 1995).

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2.11 Remediation

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2.12 Sewers, Soakaways & Septic Tanks

Overview

Sewers, soakaways and septic tanks can cause contamination of groundwater as a result of the discharge of waste water or sewage directly to the subsurface environment. As such they represent potentially serious sources of pollution in areas where groundwater is abstracted for use. Both septic tanks and soakaways are intentionally designed to convey waste water and sewage to the subsurface whilst exfiltration from leaking sewers and cess pits is an unintentional phenomenon. The waste water conveyed to the subsurface by these systems may contain contaminants ranging from human waste to industrial chemicals. Relatively little current research is being carried out in this area. That which has been done indicates that these systems are responsible for a significant degree of contamination and pollution in both rural and urban areas. However, the risk these contaminants pose must be weighed against the benefit of enhanced recharge facilitated by these services which might otherwise be lost from the groundwater phase of the hydrological cycle.

Recent / Current Research Projects	Status and Contacts
• The Impact of Cities on the Quality and Quantity of their Underlying Groundwater (and Urban and Rural Sources on Nitrates).	• 1994-1997. EPSRC, EA, (Severn Trent), Stanton plc, and MAFF funding, (contact Prof. D Lerner at Bradford University).
• The Impact of Sewers on Urban Groundwater Quality.	• 1992, Industrial sector funding (Stanton Plc.), (contact Prof D Lerner at Bradford University).
• Reliability of Sewers in Environmentally Sensitive Areas	• 1994-1995, CIRIA, EA and Water Co, funding, (contact Prof. D Lerner at Bradford University).

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See also: Microbiological Contaminants

2.12 Sewers, Soakaways & Septic Tanks

In the UK there is approximately one major incidence of sewage-related groundwater contamination per year. The occurrence of sewage contamination is related to the operation and structure of the waste water containment and treatment system and local hydrogeology. A summary of the major hydrogeological processes relevant to groundwater pollution from sewers, soakaways and septic tanks can be found in Box 1. Groundwater pollution issues associated with the three different wastewater containment and treatment systems are considered here separately, namely sewers, soakaways and septic tanks.

Sewers

Sewers are responsible for the unintentional discharge, via leaks, of large volumes of sewage to the groundwater below cities and lesser urbanised areas from which the sewage is initially derived. Recent studies indicate that this problem of exfiltration from sewers is likely to be common to the sewers of all cities. In those cases which have been investigated, exfiltration from sewers has been identified as a cause of serious pollution of groundwater below urban areas. Groundwater sampling has revealed the presence of microbiological organisms, nitrates, and organic chemicals as the most common amongst many other contaminants. (Lerner and Tellam 1992).

Leakage from sewers can most often be attributed to their advanced age and poor state of repair. Both these features are common to the majority of the sewerage system in the UK. This represents a major challenge to the Water Service Companies who are currently embarked on a major programme of capital expenditure in order to comply with increasingly stringent environmental protection legislation. However, the vast majority of this investment has been directed toward 'end of pipe' facilities to improve the general standard of treatment at wastewater treatment plants. Far less consideration has been given to the effects of leakage into or out of the pipelines or the fate of the exfiltration from the pipelines. (Reynolds 1994). Recently however, special consideration has been given to these phenomena when they might occur in Environmentally Sensitive Areas. A research project is currently underway for CIRIA entitled 'Reliability of Sewers in Environmentally Sensitive Areas'. The study is primarily concerned with groundwater contamination resulting from exfiltration from sewers in England and Wales, the causes of sewer exfiltration and strategies for minimising problems in the future with special reference to environmentally sensitive areas.

BOX 1: Major Hydrogeological Processes Relevant to Sewers, Soakaways, & Septic Tanks:

Soil Processes	Attenuation capacity of the soil is a key factor in the efficient functioning of a septic tank system.
Unsaturated Flow and Transport	The above systems all commonly result in discharges of waste water or sewage to the unsaturated zone. Flow rates and direction within the unsaturated zone may therefore have a significant influence on the extent and shape of the plume of contamination.
Microbiology	The attenuation capacity of the soil with respect to sewage effluent is determined to a large degree by its microbiological content.

2.12 Sewers, Soakaways & Septic Tanks

(Sewers which are linked to soakaways are considered in the following paragraph together with soakaways).

Soakaways

There are very few examples of recent environmental studies or research into the environmental impacts of soakaways. Soakaways, like septic tanks, are designed to convey waste water or sewage to the subsurface environment. They are common in both rural and urban environments and may typically serve to convey surface runoff from roads or urban developments thus preventing flooding which might otherwise occur. Less commonly, soakaways of a different design are utilised in rural areas to dispose of partially treated mains collected sewage or agricultural effluents.

Where soakaways are sited on vulnerable aquifers, they are often used in combination with interceptors designed to entrap a range of contaminants, for example oil, whilst still allowing the soakaway to operate normally. Such interceptor/soakaway systems are commonly used along major roads and industrial sites. However, unless the interceptor or trap is emptied with sufficient frequency, the contaminants contained in the trap may build up only to be released via the soakaway during heavy storms. Further information on interceptors and attempts to improve their efficiency is given in NRA (1996).

Military sites, industrial sites and stormwater sewers connected to soakaways have all recently been cited in the literature as potential sources of serious groundwater contamination. This has lead to recommendations for further research and proposals for the future development of environmentally safer systems (Mikkelsen, *et al* 1994).

Septic Tanks

Like soakaways, septic tanks are designed to discharge domestic, agricultural or light industrial liquid effluent to the unsaturated zone usually in rural areas where connection to mains sewerage is impractical. Most typically they serve single or small groups of dwellings. The septic tank system is composed primarily of two components: the septic tank which traps any settlement solids and floating grease contained in the sewage, and the subsurface disposal system (trench bed) which receives the liquid effluent from the tank and conveys it to the soil. Once in the soil the effluent is usually subject to aerobic decomposition and to physical and chemical removal of suspended and dissolved solids. Thus these systems rely heavily upon the attenuation properties of the soil to which they discharge. Their efficient functioning also depends upon regular emptying of the tanks to prevent overload of settlement solids.

An alternative to the septic tank is the cess pit which is designed to operate as a storage tank for sewage. Cess pits require periodic emptying and, older masonry designs in particular, require considerable maintenance to ensure they remain water tight. Leaks from cess pits are potentially much more polluting than discharges from septic tanks as they are designed only to store and not to treat sewage effluent.

The most common contaminants found in groundwater below these systems include bacteria, viruses, and nitrates. Contamination of groundwater and pollution of private water supplies from septic tanks and leaking cess pits is common in rural areas due to a number of factors including inappropriate use, poor siting (often close to wells) and inadequate maintenance.

2.12 Sewers, Soakaways & Septic Tanks

Site specific evaluation is required to determine the suitability of a site to receive a septic tank. An evaluation will include an assessment of the attenuation capability of the soil, the infiltration capacity of the site, the depth to the watertable, aquifer permeability and the proximity of local groundwater abstractions.

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2.13 Source Protection

Overview

In 1992 the NRA published 'Policy and Practice for the Protection of Groundwater'. The document provides guidelines outlining the NRA's statutory duties to protect groundwater quality and resources, and for implementing the 1991 Water Resources Act, and relevant EC regulations. Two key elements of the policy document were: a programme to classify and map groundwater vulnerability; and a programme to delineate protection zones around groundwater sources. The main aim of the protection zones is to enable the EA to provide consistent and uniform guidance to planning and waste disposal authorities on the siting of potentially polluting activities, or means of their containment. The zones are also used to help define areas of aquifers which require protection from nitrates. A standard methodology to define inner, outer, and total catchment protection zones using computer models was developed in 1991. A programme of application of this methodology to groundwater abstractions around the UK has led to greater awareness of the issues involved and scrutiny of the methods used. The EA's zone delineation programme is largely complimentary to the source protection initiatives of the Water Service Companies and smaller water companies, many of whom have carried out risk assessments on potential sources of pollution within the catchment areas of groundwater sources.

Recent / Current Research Topics	Status and Contacts
• Kilham and East Ness Groundwater Tracer Studies to Test Travel Times of Modelled Protection Zones.	• Ongoing since 1994. EA North East Region in conjunction with BGS (Contact Dr D S Chadha at BGS).

Key References:

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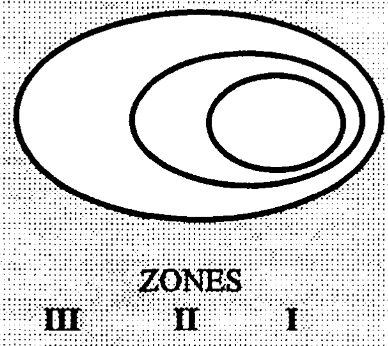
See Also: Vulnerability

2.13 Source Protection

Classification and mapping of the groundwater vulnerability zones is based on a procedure developed from land surface zoning work by the BGS (Adams and Foster 1992). The procedure is based on two independent elements: 1) Division of the land based on intrinsic vulnerability (see section 2.13), which relates to protection of groundwater resources, and 2) subdivision of the recharge capture area of individual sources into inner, outer and catchment protection zones (see Box 1), in which potentially polluting activities are strictly controlled.

BOX 1: GROUNDWATER PROTECTION ZONES - SUMMARY



Inner Zone I - Defined by 50 day travel time (min 50 metre radius)

Outer Zone II - Defined by 400 day travel time or 25% of source catchment area, based on protected yield, whichever is larger.

Source Catchment Zone III - Area needed to support protected yield from long-term recharge.

The system adopted by the EA for individual source protection zones uses steady-state computer models (FLOWPATH or MODFLOW/MODPATH) where sufficient data is available, and manual methods in areas of limited data. Research into methods of defining the uncertainty within the catchment zones is ongoing, and recently published work includes Fermor *et al.* 1995; and Evers and Lerner 1995. A comprehensive guide to the general principles and procedures for GPZ definition was published in 1995 with an accompanying manual detailing protection zone methodology (Keating and Packman, 1995). The implementation sequence of the EA GPZ programme is presented in Box 2.

The GPZ programme will help to protect aquifers by restricting future polluting activities, however there is a legacy of existing pollution, particularly in urban areas, which will continue to affect groundwater quality. In addition, the standard GPZ methodology may not be suitable for certain types of sources and aquifers. Springs and small sources have been identified by the EA as requiring careful consideration and complex or layered aquifers may also require alternative models or methods.

More specific research includes work into the refinement of modelled travel times in the fractured Corallian and Chalk aquifers in the EA North East Region and source protection work carried out by the Water Service Companies. These projects are briefly described below.

1. Refinement of modelled travel times in the fractured Corallian and Chalk aquifers in the Northumbrian & Yorkshire EA Regions (contact Dr DS Chadha at the BGS) - the first stage of the research was focused on the investigation of the characteristics of the Corallian and Chalk aquifers by geological logging and dilution testing. A series of tracer tests to determine actual groundwater travel times in these aquifers around specific groundwater sources is planned for 1996. Observed travel times will then be available for comparison with modelled travel times. This research is likely to have a bearing on the confidence which is placed upon modelled protection zones in fractured aquifer systems.

2.13 Source Protection

2. Source protection work carried out by the Water Service Companies - this research is largely complimentary to the EA's zoning programme. In the main, the water companies have pursued risk assessments based upon potentially polluting features or activities found within the catchment areas of their own groundwater sources. The methodology of assessments varies across the country.

Further work is required to develop greater understanding of groundwater flow and transport to supply sources. This will allow source protection without unnecessary restrictions on land use. Research leading to the refinement of the national approach to source protection zone definition is also required. This will involve assessment of the degree of confidence in protection zones defined for variable aquifers or uncertain parameters. This will include, for example, the significance of using steady-state models when aquifer behaviour is transient due to recharge variations, and the applicability of the modelling approach to fractured or karstic aquifers.

BOX 2: The Implementation of the EA Source Protection Policy.

Phase I - 'First pass' GPZ definition (750 sources).1991.

GPZ II - Second phase refinement of GPZs for 150 priority sources which were candidates for Nitrate Vulnerable Zone (NVZ) and Nitrate Sensitive Area (NSA) designation. 1994-95.

GPZ III - Third phase definition of GPZs for around 1250 public supply, non-public potable, and sensitive commercial sources. 1995-97.

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2.14 Vulnerability

Overview

The NRA Policy and Practice for the Protection of Groundwater (1992) identified the classification of groundwater vulnerability as a key factor in the protection of regional groundwater resources. The vulnerability of the groundwater depends on a number of factors, including the type and depth of soil, the physical, chemical, and biological properties of the aquifer, the thickness of the unsaturated zone, the amount of recharge, and also the contaminant of interest. The vulnerability maps will allow planners, developers, and regulatory bodies to make better informed judgements on the location or means of containment of potentially polluting new developments.

Recent / Current Research Projects	Status and Contacts
• Mapping of Aquifer Vulnerability in England and Wales at 1:100,000 scale.	• 1994-1996. EA, HMSO (Conducted by The Soil Survey and Land Research Centre at Cranfield University and the BGS)
• Comparative Soil Leaching Studies using Lysimeters.	• 1994-1996, MAFF funding (contact C Brown at the Soil Survey and Land Research Centre).

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See also: Source Protection

2.14 Vulnerability

Groundwater vulnerability is the degree to which an aquifer's saturated zone is prone to the vertical penetration of pollutants from the land surface. Identification of groundwater vulnerability has been recognised as a key factor in groundwater protection and aquifer vulnerability mapping has been incorporated into the EA's national policy on groundwater protection.

Groundwater vulnerability maps of the UK, produced by the HMSO, under the EA's groundwater protection policy were published at the end of 1995. The mapping methodology used was developed from research carried out by the BGS on land surface zoning (Adams and Foster 1992), and the mapping conducted by the Soil Survey and Land Research Centre at Cranfield University.

Factors which define the vulnerability of groundwater are presented in Box. 1. Vulnerability also depends on the contaminant in question (Harris and Skinner 1992). The susceptibility of contaminants to attenuation and degradation, and the concentrations at which they are classed as pollutants must all be considered. Vulnerability to nitrates is at present the major concern, however other contaminants must also be considered (e.g. DNAPL, acidification, pesticides, micro-organisms).

BOX 1: Factors which Define Vulnerability of Groundwater

- Presence and nature of overlying soil
- Presence and nature of drift
- Nature of geological strata
- Depth to unsaturated zone

Groundwater vulnerability maps have also been produced by Hiscock *et al.* (1995) using a GIS system to overlay soil, drift, and geological characteristics. On a smaller scale, recent research by Younger *et al.* (1993) included fieldwork and modelling to assess the vulnerability to pollution of groundwater abstracted by riverside wells when river water is contaminated. The conclusions of this study indicated that in the section of the Thames assessed, low permeability stream bed sediments were an important barrier to groundwater pollution by river water. The Soil Survey and Land Research Centre at Cranfield University are currently conducting soil leaching studies using lysimeters in a programme sponsored by MAFF.

Further research is required to improve our understanding of critical physical, chemical and biological factors controlling the transport and attenuation of different pollutants as a function of soil, geological, and hydrogeological conditions. The FWR, 1995 report recommends the development of management tools to reduce pollution risk to vulnerable groundwater sources without imposing unnecessary restrictions on economic activity. This may include research into risk based classification of activities which are potentially polluting to groundwater, and the development of predictive transport models.

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List of Abbreviations

AMD	Acid Mine Drainage
API	American Petroleum Institute
BBSRC	Biotechology & Biological Sciences Research Council
BGS	British Geological Survey
BRGM	Bureau de Recherches Geologiques et Minieres (The French Geological Survey)
BTEX	Benzene, Toluene, Ethylbenzene and Xylene compounds
CIRIA	Construction Industry Research and Information Association
CLR	Contaminated Land Report
CONCAWE	The Oil Company's Organisation for Environmental and Health Protection
CRIB	Current Research in Britain directory
DoE	Department of the Environment
DNAPL	Dense Non-Aqueous Phase Liquid
EA	Environment Agency
EC	European Commission
EPA	Environmental Protection Agency (USA)
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
FWR	Foundation for Water Research
GIS	Geographic Information System
GPZ	Groundwater Protection Zones
GW	Groundwater
HLW	High-Level Waste
HMIP	Her Majesty's Inspectorate of Pollution
HMSO	Her Majesty's Stationary Office
ICE	Institution of Civil Engineers
IH	Institute of Hydrology
ILW	Intermediate-Level Waste
LLW	Low-Level Waste
LNAPL	Light Non-Aqueous Phase Liquid
MAFF	Ministry of Agriculture, Fisheries and Food
MTBE	Methyl-tertiary-butyl ether
NAPL	Non-Aqueous Phase Liquid
NSA	Nitrate Sensitive Area
NERC	Natural Environmental Research Council
NRA	National Rivers Authority
NRPB	National Radiological Protection Board
NVZ	Nitrate Vulnerable Zone
PAH	Polynuclear Aromatic Hydrocarbons
PCE	Tetrachloroethane
PFA	Pulverised Fuel Ash
PHSL	Public Health Services Laboratory
R&D	Research and Development
SSLRC	Soil Survey and Land Research Centre (Cranfield University)
TCA	Tetrachloroethane

TCE	Trichloroethene
UK	United Kingdom
USEPA	United States Environmental Protection Agency
WRc	Water Research Centre

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Index by Research/Funding Organisation

LIST OF CONTACTS

Alloway	BJ	Reading University
Ball	SP	Imperial College
Bannister	JV	Cranfield University
Bardos	P	Nottingham Trent University
Bardsley	P	NRA - North West Region
Barker	AJ	University of Southampton
Barker	IA	British Geological Survey
Barrett	M	Birmingham University
Bashar	K	Birmingham University
Belt	S	University of Plymouth
Beven	KJ	University of Lancaster
Billet	M	University of Aberdeen
Binley	AM	University of Lancaster
Boyce	E	University of Cambridge
Bradley	G	University of Plymouth
Braithwaite	A	Nottingham Trent University
Brattan	D	University of Central Lancashire
Brewerton	LJ	British Geological Survey
Bright	M	Birmingham University
Brown	RG	University of Central Lancashire
Burgess	WG	University College London
Burns	RG	University of Kent
Butler	AP	Imperial College
Cabrera	JG	University of Leeds
Cachandt	G	NRA
Cain	R	University of Newcastle Upon Tyne
Chandratillake	MR	University of Manchester
Chilton	J	British Geological Survey
Chowdhry	BZ	University of Greenwich
Christensen	PA	University of Newcastle Upon Tyne
Clark	L	WRc
Colston	BJ	University of Manchester
Cotter-Howells	JD	University of Aberdeen
Crawford	M	British Geological Survey
Cresser	M	University of Aberdeen
Crittenden	BD	University of Bath
Curtis	T	University of Newcastle
Davey	Ian	NRA
Denner	JM	Deparytment of the Environment
Diaz	MA	Imperial College
Donaldson	JD	Brunel University
Dunham	SJ	Institute of Arable Crops research
Edmunds	WM	Bristol University
Elliot	S	University of Exeter
Elliott	D	University of Newcastle Upon Tyne
Flavin	R	NRA
Fleming	G	Strathclyde University
Fletcher	SE	University of Manchester
Foster	SSD	British Geological Survey
Fowles	GW	University of Reading
Fuge	R	University of Aberystwyth
Gale	IN	British Geological Survey
Gilmour	RA	Strathclyde University
Goodwill	IM	University of Leeds
Gray	R	WS Atkins Consultancy
Green	BMR	NRPB
Greswell	R	Birmingham University
Grey	Ian	NRA
Griffiths	JS	University of Plymouth
Gronow	JR	DoE
Gunn	J	University of Huddersfield
Haile	S	University of Newcastle
Halliday	D	Birmingham University
Hammett	A	University of Newcastle Upon Tyne
Hancock	IC	University of Newcastle
Harman	R	Institute of Arable Crops research
Harris	B	NRA
Harrison	I	Nottingham Trent University
Hawkes	DD	Birmingham University
Head	I	University of Newcastle
Hellawell	E	University of Cambridge
Higgo	R	British Geological Survey
Hiscock	KM	University of East Anglia
Hoffman	SMA	University of Manchester
Hoggart	C	Sir William Halcrow and Partners
Holder	JV	University of Central Lancashire
Hooker	PJ	British Geological Survey
Hornung	G	University of Leeds
Howarth	CR	University of Newcastle Upon Tyne
Hudson	MJ	University of Reading
Hyland	R	University of Huddersfield
Jefferies	N	AEA Technology
Johnston	PM	Imperial College
Jones	DM	University of Newcastle
Jones	KC	University of Lancaster
Jones-Lee	MW	University of Newcastle upon Tyne
Killham	K	University of Aberdeen
Kinniburgh	DG	British Geological Survey
Kitching	R	British Geological Survey
Kleinert-Smith	U	Birmingham University
Kolaczkowski	ST	University of Bath
Laidlaw	IMS	University of Aberystwyth
Lattey	S	University of Leeds
Lawrence	AR	British Geological Survey
Leharne	SA	University of Greenwich
Lerner	DN	University of Bradford
Lester	JN	Imperial College
Limbert	E	York University
Littleboy	A	UK Nirex Ltd
Lloyd	JW	Birmingham University
Mackay	R	University of Newcastle Upon Tyne
Mather	JD	Royal Holloway
Matthias	D	NRA
McArthur	JM	University College London
McDonald	M	Strathclyde University
McGhee	I	University of Kent
McGrath	SP	Institute of Arable Crops research
Meharg	A	Institute of Terrestrial Ecology
Metcalfe	R	British Geological Survey
Miles	JCH	NRPB
Monhemius	AJ	Imperial College
Morton	G	University of Central Lancashire
Nathaniel	P	Nottingham Trent University
Needham	S	Birmingham University
Newson	M	University of Newcastle Upon Tyne
O'Connell	E	University of Newcastle Upon Tyne
Oakes	D	WRc
Oliver	S	University of Cambridge
Owens	NPJ	University of Newcastle
Palmer	RC	Soil Survey & Land Research Centre
Paton	G	University of Aberdeen
Perry	R	Imperial College
Phillips	CV	University of Exeter
Pollard	SJT	Aspinwall & Company
Powrie	W	University of Southampton
Price	GJ	University of Bath

Prime	D	University of Manchester
Revans	A	University of Plymouth
Reynolds	P	WRc
Reynolds	PP	NRA - North West Region
Rhead	M	University of Plymouth
Robinson	VJ	University of Manchester
Rogers	KP	University of Aberystwyth
Rowland	SJ	University of Plymouth
Savvidou	C	University of Cambridge
Scott	K	University of Newcastle
Smith	FM	University of Aberystwyth
Smith	J	NRA
Spears	DA	University of Sheffield
Stentiford	EI	University of Leeds
Stewart	D I	University of Leeds
Stuart	ME	British Geological Survey
Swindalle	JW	Queens University
Tellam	JH	Birmingham University
ten Brummeler	E	Heidemij Realisatie
Thomas	C	NRA
Thornton	SF	Birmingham University
Tranter	M	Bristol University
Trier	C	University of Plymouth
Verstraete	W	University of Gent
Walsh	JN	Royal Holloway
Walton	NRG	University of Portsmouth
Watkins	D	University of Exeter
West	JM	British Geological Survey
Wheater	HS	Imperial College
Williams	AT	University of Glamorgan
Worsfold	P	University of Plymouth
Younger	P	University of Newcastle Upon Tyne
Zaba	B	NRA R&D Department

CIRIA
Department of Trade and Industry
EPA
EPSRC
MAFF
NERC
Water Utilities