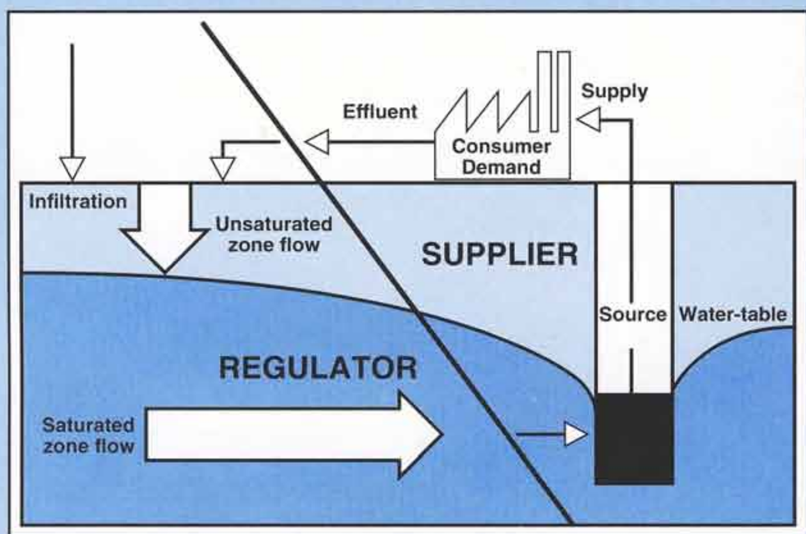
GROUNDWATER IN THE UK

A Strategic Study

Issues and research needs



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UK Groundwater Forum

June 1995
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Report prepared by:

Hydrogeology Group
British Geological Survey
Maclean Building
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
UK
Telephone: (01491) 692 351
Fax: (01491) 692 345

to whom technical enquiries should be addressed.

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UK Groundwater Forum

Overall objective

To promote dialogue , consultation and partnership between all public and private parties with an interest in groundwater resources with primary emphasis on the sharing of research ideas, resources and products, and secondary emphasis on the discussion of questions of data, policy and standards, in order that groundwater issues are identified and resolved in the most cost-effective way, through cooperative efforts, and the findings are widely disseminated.

Specific objectives

- to act as a vehicle for dialogue and consultation;
- to maintain a shared user-led National Groundwater R&D Agenda;
- to promote public/private partnerships in R&D consortia;
- to promote collaboration between research organisations;
- to disseminate research widely amongst researcher and user communities;
- to promote public information and awareness; and
- to promote a unified approach to Europe.

Chapter 13 of the Report includes further discussion of these objectives, together with recommendations concerning organisation and membership of the Forum.

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Groundwater in the UK: Issues and Research Needs

Main Author/Editor:	David Grey*		
Contributing Authors:	David Kinniburgh* John Barker* John Bloomfield*		
Steering Committee:	Andrew Skinner	NRA	(Chairman)
	Cliff Tubb	NRA	
	Rex Agg	FWR	
	Brian Connorton	WSA/WCA	
	Stephen Foster	NERC/BGS	
	David Grey	NERC/BGS	
	John Bloomfield	NERC/BGS	(Secretary)

* Hydrogeology Group, British Geological Survey, Maclean Building, Wallingford, Oxfordshire, OX10 8BB
The British Geological Survey, a component institute of the Natural Environment Research Council, is the national centre for geological and hydrogeological survey, research and data.

Acknowledgements

This Report is based on the findings of extensive consultations with a very wide range of individuals and institutions. The Report's annex lists those who: responded to a questionnaire (7-9/94); participated in the Groundwater Forum (9/94); participated in the regional seminars (Scotland/Northern Ireland 2/95, and England/Wales 2/95); participated in the Science Seminar (1/95); and authored or reviewed issues papers (to be published separately as the Groundwater Issues Report). The significant intellectual inputs of everyone listed are acknowledged, as are the efforts of others who may have been inadvertently omitted, for which we apologise.

In addition, written or graphic contributions were also made to the report by David Allen, John Chilton, Ian Gale, Nick Robins, Anna Mathews, Linda Brewerton, Roger Calow and John Talbot, all of BGS. The Steering Committee provided substantive inputs and guidance from inception to completion of the Study, including significant editorial contributions.

Foreword

This Study arose out of the realisation that groundwater research in the UK was at risk of becoming too fragmented because of a lack of strategic interlinking between major research funders. Water industry reorganisation in England and Wales had led to a divergence because of the differing priorities of the regulator and the utility companies. An increasing interest in groundwater in Scotland and Northern Ireland was not benefiting from the experience of groundwater management in areas of similar geology in England and Wales. Overall there was concern that the dispersed institutional arrangements meant that opportunities for resolving issues in the most cost-effective way through cooperative efforts were being missed.

The Study has been managed by a Steering Committee drawn from the major funders who have been enormously encouraged by the positive and constructive support received at the various meetings which have been held to take soundings and test opinions. The result is this Report on future research issues and needs for the UK as a whole, prepared on behalf of the Steering Committee by David Grey and his colleagues at the British Geological Survey.

We hope and believe that we have taken a significant step in this Study and that it will provide a framework to stem the fragmentation of research and provide a stronger and more cohesive research base, in the interests of all the various stakeholders in the management of groundwater and its effects on the environment.

We also believe that, through the community of consultees the project has established, we have identified a vehicle whereby sharing of research ideas and research resources can be encouraged and the issues and the products of research can be discussed and evaluated.

We adopted the title *UK Groundwater Forum* for the meetings we held as part of this Study. The discussion at these meetings supported the view that the initiative of the Forum should be carried forward as a loose grouping of stakeholders, who will meet from time to time, to review achievements and identify new research opportunities to potential funders. The Steering Committee and the Forum would not promote research directly, although it would expect to be able to identify and encourage opportunities for coordination and partnership. It is anticipated that its role could extend beyond a strict interpretation of research and provide a means of discussing issues of data, policy and standards which might require investigation. It would not have any independent standing, although we hope to identify a resource to support a secretariat function, which will service some of the needs identified, for example to maintain a research database and disseminate information through printed and electronic media.

On behalf of the Steering Committee I thank the many of you who contributed to the ideas and information in this Report. I hope you will review the products and use your influence and resources to contribute to solving the priority problems identified. If you have any comments and suggestions, or merely wish to be informed of future activities of the Forum, please contact the Secretariat at the address below.

Andrew Skinner
on behalf of
The UK Groundwater Forum Steering Committee
c/o British Geological Survey
Maclean Building
Crowmarsh Gifford
Wallingford
Oxon OX10 8BB, UK.

This Report is published on behalf of the sponsoring agencies, Natural Environment Research Council, National Rivers Authority, Foundation for Water Research, Water Services Association, Water Companies Association and the Scotland and Northern Ireland Forum for Environmental Research, but any opinions expressed within the Report are those of the authors and not necessarily of the sponsors.

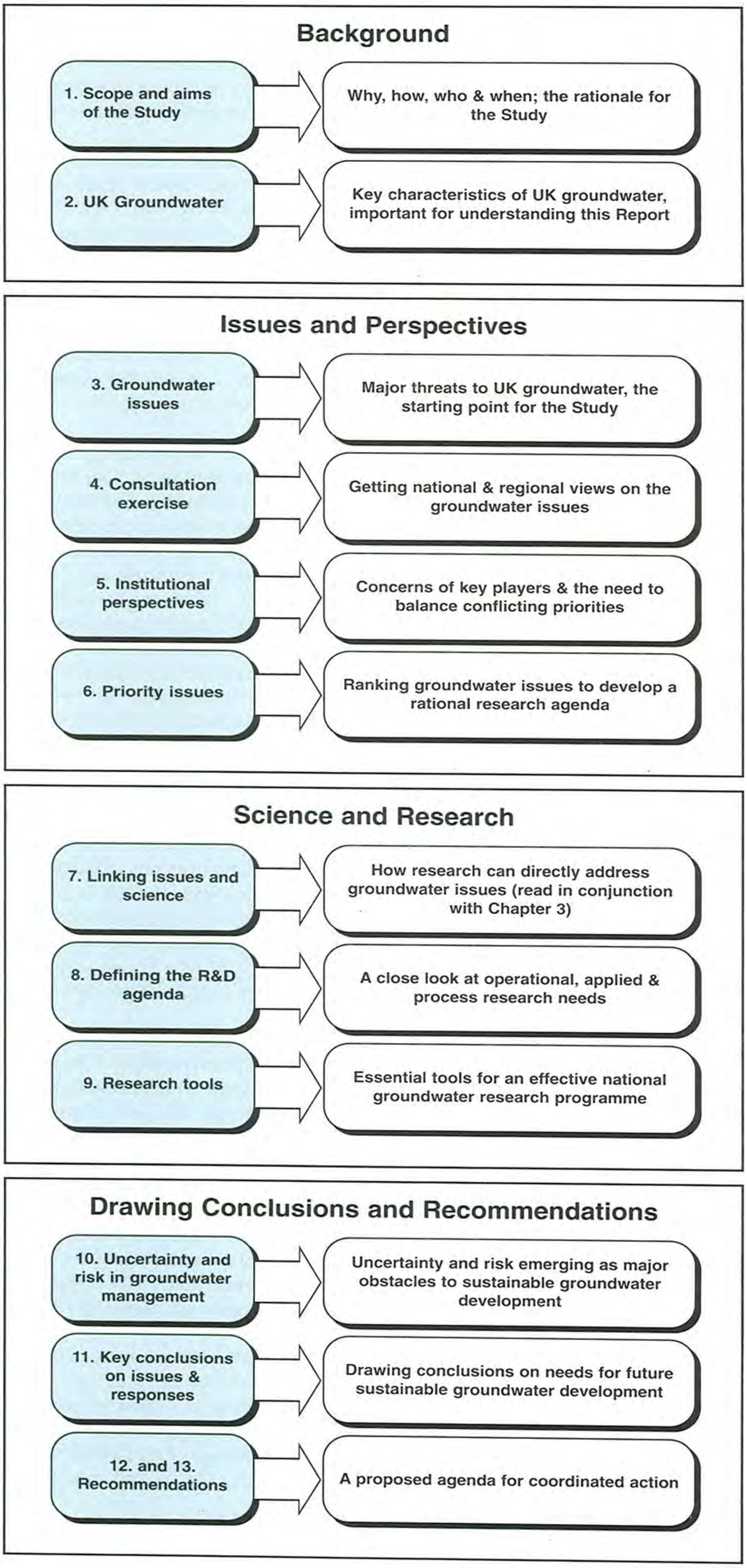
A Guide to the Report

The Report is about the UK's groundwater resources. It gives a broad overview of those resources. It then identifies a range of issues of concern to all those with an interest in groundwater - government, the regulators, the water industry, other industries and lobby groups, and water users. The Report goes on to describe the links between these issues and the underpinning science, describing the research and development needs to address the most important of the issues. The Report then ends with conclusions and provides recommendations for action, which include implementation of a coherent and cost-effective R&D agenda, focused on the perceived needs of the users themselves.

The Report is aimed at a diverse readership, including policy makers, regulators, water industry managers and scientists, planners, managers and scientists in other industries and in agriculture, and researchers of various disciplines. As a consequence, the Report is in part general and in part technical, containing information that some readers may find unnecessary and others may find inadequate. In addition, there is also some repetition, to ensure completeness of discrete parts of the Report. Wherever possible, boxes, figures and tables have been employed to enable readers to peruse the Report, without reading it in any detail.

In order to facilitate and encourage readers to select relevant sections of the Report, a 'map' is presented on the right. This 'map' illustrates the four themes of the Report - Background, Issues and Perspectives, Science and Research, and Drawing Conclusions and Recommendations - and indicates the scope of each of the thirteen Chapters included within these themes.

It is intended to publish an accompanying volume to this Report, providing details of each of the 'groundwater issues', entitled the 'Groundwater Issues Report'.



Executive Summary

The overall objective of the Study is to support the sustainable development of the groundwater resources of the United Kingdom, including the identification of cost-effective strategies for groundwater abstraction, protection and remediation.

The specific objectives of the Study are twofold. The first objective is to identify scientific issues - threats, constraints and uncertainties - in groundwater management and use in the UK now and in the foreseeable future, from the perspectives of the public and private sectors, and in the light of current or anticipated regulations or policies. The second objective is to define a research agenda for all groundwater research customers that adequately addresses the issues whilst ensuring an underpinning knowledge of UK aquifers. The Study achieves these objectives through identifying and describing: the issues affecting groundwater in the UK; the perspectives of the different interested and responsible institutions; the science underpinning the issues; and a research agenda to address the issues of primary concern.

Extensive consultation among the full range of stakeholders has been undertaken to define and debate the primary issues and appropriate responses. The consultation has been achieved through a number of mechanisms. Firstly, face-to-face meetings have been held with representatives from water service and supply companies, water regulators and government agencies. Secondly, questionnaires were sent to a wide range of individuals and institutions with interests in groundwater development, and about 100 responses were received giving information on current or recent R&D activities and identifying groundwater issues of most concern. Thirdly, a UK Groundwater Forum has been established to provide a mechanism for dialogue on current and future scientific issues in groundwater among the main parties with an interest in UK groundwater. Forum meetings have included an initial meeting in September 1994 with members of representative organisations from the public and private sectors, academia, and professional and industry associations. A science seminar was held in January 1995 with representatives from research organisations and universities with interests in UK groundwater research, with the purpose of establishing rational scientific linkages between the issues arising from the consultation exercise and the R&D priorities. Two national seminars were then held in Scotland (for Scotland and Northern Ireland) and in England (for England and Wales) in February 1995, to discuss the first draft of this Report. The purpose of these seminars was to seek broad consensus on groundwater issues, R&D needs and strategies, and to invite specific comments for incorporation into the final report. Over 150 different people from a very wide range of public and private organisations participated in the various Forum meetings.

Thirty-one issues affecting groundwater resources have been identified as a result of the consultation exercise. These include issues related to groundwater quantity, such as low flows, sustainable yield, rising water levels, unregulated rural supply, wastewater re-use, and borehole efficiency, and issues related to groundwater quality, such as acid mine drainage, contaminated land, landfill, nitrate, pesticides, and sludge use. In addition, there are other issues that impinge on both groundwater quality and quantity, for example climate change and wetland conservation. A number of issues, for example contaminated land, landfill, nitrate, pesticides and source protection, were seen as primary issues of concern, regardless of the affiliation of the consultees. However, as a result of the consultation exercise it was evident that there are widely varying regional and institutional perspectives on groundwater issues.

Regional perspectives can be classified into 'upland' and 'lowland' regions of the UK. Upland areas consist of much of Scotland, Wales, Northern Ireland, south west England, and parts of other areas of England; lowland areas consist of southern and eastern England with parts of other areas. Key groundwater issues in upland UK include the impact of water-level rebound in abandoned mines, the effects of quarrying activities below the water table and contaminated land on groundwater, the impact of sewage sludge disposal and diffuse agricultural pollution, including sheep dip disposal, on shallow groundwaters and small rural supplies. Key groundwater issues in lowland UK include the environmental impact of groundwater abstraction, including baseflows, the effectiveness of nitrate application controls and source protection zones, the prediction of groundwater behaviour in drought, and the extent and persistence of pesticide contamination.

Institutional perspectives can be broadly classified into those of government, regulators, water service and supply industry, and others. Central government is responsible for national water policy, has ultimate responsibility for water regulations and functions and is also responsible for ensuring the implementation of appropriate and relevant EC directives. The perspectives of local government agencies relate to their responsibilities for planning. In response to the questionnaire the most important groundwater issue for local government was landfill. The water regulators (NRA in England and Wales, the River Purification Boards in Scotland, and DoE Northern Ireland) have statutory duties that require them to protect and improve the water environment through effective management of water resources, and by substantial reductions in pollution. Regulators apply the precautionary principle - where significant environmental damage may occur but knowledge on the matter is incomplete, decisions made and measures implemented should err on the side of environmental protection. However, they seek to do this whilst maintaining a balance between needs of the environment and those of the abstractors. Low flows, aquifer vulnerability, wetlands, sustainable yield, pesticides, NAPLs and contaminated land are the most significant groundwater issues for regulators in lowland UK. The water service industry is concerned with maintaining a predictable, efficient supply of clean water from its existing sources, to enable them to meet the growing demands of their customers. From the perspective of the water industry, the most significant issues are therefore quality and quantity concerns at their water supply sources, eg pesticides and nitrate, low flows, borehole efficiency, source protection and reliable yield. In addition, environmental non-governmental organisations, industry (user) groups, the research community and the general public all have differing perspectives on specific groundwater issues. A widely-held public perception is that groundwater development is a primary culprit for environmental degradation and there is little appreciation of the benefits of groundwater use (reliability, security, quality and low cost).

Defining a practical groundwater research and development agenda arising from the issues is the second objective of the Study. As a first step, the group of 31 issues is narrowed down to a priority list of 14 issues on the basis of their importance and whether or not they are of increasing concern. Secondly, the science underpinning the issues is then briefly reviewed, primarily in terms of the relationship between the issues and dominant hydrogeological processes, of which eight are described. For example, understanding many of the issues involves a detailed knowledge of groundwater flow in the unsaturated and saturated zones and of chemical reactions that occur in aquifers. Thirdly, the principal research requirements are summarised for each of the 14 priority issues, setting out research objectives, operational research requirements, applied research and data needs and the underpinning hydrogeological processes in each case. Cutting across the issues, there is a clear overlap and therefore the operational research, applied research and hydrogeological research needs are also examined generically. Finally, research tools, such as monitoring, field experiments, modelling and databasing are discussed and needs identified.

Uncertainty and risk in groundwater management and development is a subject of increasing concern for both the water industry and the regulators, emerging frequently in the consultations. Groundwater management by the regulators, in accordance with the precautionary principle, will incorporate wide but appropriate margins of safety when there is significant uncertainty. Similarly, investment decisions by the industry will err on the side of safety, within the constraints imposed by price caps, given uncertainty and the need to ensure compliance. Consequently, management tools to reduce uncertainty would allow more sensitivity in decision making, with potential major economic gains through confidence in more finely-balanced decisions regarding groundwater quantity and quality management. The application of risk analysis tools to groundwater management in the UK has to date been limited, and their development and adoption is recommended.

Key conclusions are drawn from the consultations, the review of perspectives and the analysis of research needs. The concept of sustainability in groundwater development needs to be clarified, as it can be interpreted in numerous ways. In order to do this, economic questions on groundwater resources degradation (both quantity and quality) and the associated impacts on society and ecosystems need to be answered, requiring a rare level of interdisciplinary analysis. There is a sharply polarised debate regarding the relative costs and benefits of protecting 'upstream' or treating 'downstream' and analysis of the issue is important. Similarly, there are possible opportunities for further optimisation of groundwater resource development, including conjunctive use, compensation pumping and innovative use of aquifer storage potential. An important conclusion is that enhanced public awareness of groundwater and its role in our daily lives and the landscape, and public participation in decision making on some of the more intractable ethical questions, could make a significant contribution to sustainable groundwater management.

Recommendations of the Study fall within two broad themes:

1. *A National Groundwater R&D Agenda* is proposed with the following broad elements: reduction of uncertainty and risk in groundwater management through targeted monitoring and data collection; the establishment of coupled economic, hydrogeological and ecological studies in the interdisciplinary analysis of environmental impacts and economic costs and benefits; a focused, longer-term R&D agenda based on the 14 primary groundwater issues identified by the Study; and development of demonstration sites and catchments building in an 'opportunistic' way on existing or planned operations or site investigations, to allow a wide range of groundwater issues to be addressed by different researchers and research customers. A priority, shorter-term R&D agenda is recommended, with 26 projects identified, including 11 scoping studies. This agenda would supplement ongoing and planned R&D.

2. *The UK Groundwater Forum*, which was initiated by the Study and received widespread support, should be sustained and extended, as a loose grouping of stakeholders. The overall objective of the Forum should be: *to promote dialogue, consultation and partnership between all public and private parties with an interest in groundwater resources, with primary emphasis on the sharing of research ideas, resources and products, and secondary emphasis on the discussion of questions of data, policy and standards, in order that groundwater issues are identified and resolved in the most cost-effective way through cooperative efforts, and the findings are widely disseminated.* The specific objectives of the Groundwater Forum would be:

   - to act as a vehicle for dialogue and consultation;
   - to maintain a shared user-led National Groundwater R&D Agenda;
   - to promote public/private partnerships in R&D consortia, minimising the duplication of effort whilst maximising returns on research;
   - to promote collaboration between research organisations;
   - to disseminate research details and results widely amongst the researcher and user communities;
   - to promote public information and awareness, and
   - to promote a unified approach to Europe.

SCIENCE AND RESEARCH (cont'd)

DRAWING CONCLUSIONS

List of abbreviations used in this Study

AFRC	Agricultural and Food Research Council
AMD	Acid Mine Drainage
AMP	Asset Management Plan
ASR	Aquifer Storage Recovery
BGS	British Geological Survey
BMNH	British Museum of Natural History
BNFL	British Nuclear Fuels Ltd
CAP	Common Agricultural Policy
CIRIA	Construction Industry Research and Information Association
CORDIS	Community Research and Development Information Service
CRIB	Current Research in Britain directory
CSFI	Centre for the Study of Financial Innovation
DoE	Department of the Environment
DoE/NI	Department of the Environment, Northern Ireland
DNAPL	Denser than water Non-Aqueous Phase Liquid
DSS	Decision Support System
DWI	Drinking Water Inspectorate
EC	European Commission
EPA	Environmental Protection Agency (USA)
ESF	European Science Foundation
EU	European Union
FWR	Foundation for Water Research
GIS	Geographical Information System
GW	Groundwater
HLW	High-Level Waste
HMIP	Her Majesty's Inspectorate of Pollution
IH	Institute of Hydrology
ILW	Intermediate-Level Waste
LLW	Low-Level Waste
LNAPL	Lighter than water Non-Aqueous Phase Liquid
MAC	Maximum Admissible Concentration
MAFF	Ministry of Agriculture, Fisheries & Food
NAPL	Non-Aqueous Phase Liquid
NSA	Nitrate Sensitive Areas
NERC	Natural Environment Research Council
NGO	Non-Governmental Organisation
NRA	National Rivers Authority
NRPB	National Radiological Protection Board
NVZ	Nitrate Vulnerable Zone
ODA	Overseas Development Administration
OFWAT	Office of Water Services
R&D	Research & Development
RPB	River Purification Board
RTD	Research and Technological Development Programme
SERC*	Science & Engineering Research Council
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
UK	United Kingdom
USA	United States of America
WCA	Water Companies Association
WSA	Water Services Association
WRc	Water Research Centre

*Now **EPSRC** Engineering and Physical Sciences Research Council

1. Scope & aims of the Study

Rationale

This Study is about the United Kingdom's groundwater resources: what is known about them, what is not known and what needs to be known in the context of sustainable exploitation and/ or responsible management. The UK's groundwater resources are of very great importance; they provide a local and least-cost source for a significant proportion of total public water supply (in many areas exceeding 50%), they preserve dry weather river flows and they maintain important wetland habitats.

Locally, rising water demand introduces the risk of bringing these functions into conflict as groundwater abstraction affects streamflow and wetlands. Urban, industrial and agricultural development are invariably accompanied by the risk of groundwater contamination or pollution. In addition, the reduction in pumping of groundwater in some areas (eg in some cities and mining areas) is resulting in rising groundwater levels, jeopardising both infrastructure and the environment.

Sustainable groundwater management and use should enable optimal resource development, constrained by limiting environmental impacts. It also requires the protection of aquifers from contamination, while not unduly restricting economic activity. Trade-offs are implicit in minimising the costs and maximising the collective benefits to the economy, to the environment and to water users. While these decisions are influenced by the political climate, they must be informed by comprehensive understanding of groundwater systems, ie both aquifers and surface-aquifer connections which are difficult to analyse and their behaviour difficult to predict. Groundwater systems normally respond slowly to change, including remediation, and as a consequence, problems are often long term and very costly to rectify, once detected. Remediation is not only often long term and costly, it is sometimes not technically possible.

Groundwater research, both short term and strategic, provides an essential underpinning to the sustainable development of the UK's groundwater resources and to the identification of cost-effective strategies for groundwater abstraction, protection and remediation. Strategic research is needed to fill important gaps which still remain in the basic understanding of the United Kingdom's aquifers and groundwater resources, in a manner which provides value for money and is cost-effective. This Study seeks to provide a comprehensive statement of the issues currently affecting groundwater resources development and associated research needs and priorities.

Genesis

The Study arose from growing concerns about the limited scope and the fragmentation of groundwater research, due in part to the institutional restructuring of the water sector over the past few years and to the tightening of R&D budgets during the recent recession. These concerns, raised in discussion between key stakeholders, including the Department of the Environment (DoE), National Rivers Authority (NRA), Water Services Association (WSA), Foundation for Water Research (FWR), Scotland and Northern Ireland Forum for Environmental Research (SNIFFER) and Natural Environment Research Council/ British Geological Survey (NERC,BGS), were set against a background of a growing environmental focus on groundwater resources and quality, increasing regulation of groundwater development, and enhanced public awareness of groundwater during the recent drought. The complex nature of some of the UK's major aquifers and the limited knowledge of their behaviour is leading to precautionary and risk-based decisions by regulators and water industry alike. Such precautionary and risk-based decisions may be significantly different if the knowledge base were greater.

Key concerns which were discussed included:

- the growing gap between and among public and private funders of research, due to different mandates and duties and therefore very different perspectives of research issues and priorities, with the risk of leaving important issues unaddressed;
- the restricted dialogue between different groundwater research commissioning institutions (both public and private), and limited ability of their staff to design and manage research programmes, due to increasing short-term financial and commercial pressures and lack of appropriate incentives, resulting in the risk of uncoordinated and inappropriate research programmes;
- the lack of clear responsibility for commissioning and funding strategic, longer-term groundwater research, which may have less immediate and direct application but nevertheless provides essential underpinning knowledge of hydrogeological processes and groundwater resources and quality;
- the reduction in field-based, longitudinal groundwater research, involving the collection, compilation and publication of data (such as in the nitrate research programme in the 1970s and early 1980s), and the increase in short-term studies which may not contribute effectively to the knowledge base; and
- limited information on groundwater research under way and completed and limited publication of results and data, partly due to increasing commercial and regulatory pressures; and thus, despite the limited budgets for R&D, reducing benefits to the community as a whole and increasing risks of duplication of research effort.

Following meetings in late 1993 among the various stakeholders listed above where these concerns were discussed, this Study was conceived to seek solutions which would bring benefits to the UK as a whole.

Objectives

The overall objectives of the Study are given in Box 1.1. Specific objectives of the Study include:

1. achieving wide consultation to identify groundwater issues; and

2. the identification of a balanced/cost-effective groundwater research programme (objectives, benefits, beneficiaries), including:

- maintenance of the quality, value-for-money and relevance of groundwater research & monitoring;
- assessment of key factors affecting sustainable use of groundwater;
- the identification of needs for technology development;
- assessment of the impacts of environmental change on groundwater including a consideration of strategic implications and research needs;
- assessment of the effect of uncertainty on groundwater management.

BOX 1.1 Overall Objectives of the Strategic Study

1. Identify scientific issues in groundwater management and use in the UK
   - now and in foreseeable future,
   - from perspectives of responsible public/private parties,
   - in light of current/anticipated regulations/policies,
2. Define research agenda for all groundwater research customers and researchers
   - to address the issues,
   - to ensure underpinning knowledge of UK aquifers.

Some definitions

For the purposes of the Study, *groundwater* is deemed to include water that has infiltrated beyond the soil zone, is moving through the unsaturated zone and the saturated zone and may emerge from the land surface, either naturally as a spring or as a result of abstraction at a water supply source. The Study seeks to include all natural or artificially-induced processes affecting or affected by groundwater, whether in the unsaturated or saturated zone or at the source (such as within a water supply borehole). Having established these boundaries somewhat arbitrarily, the Study does not extend to include 'upstream' processes, such as transpiration, or 'downstream' processes, either natural ones, such as the effects on biodiversity of groundwater flows to wetlands, or artificial processes, such as the treatment of contaminated groundwater at a groundwater supply borehole.

The Study focuses on *issues* affecting groundwater. For the purposes of the Study, an issue is:

- a threat to groundwater quality or quantity;
- a constraint on groundwater development; or
- any significant uncertainty.

The addition of opportunities (such as artificial recharge of groundwater) to the list of issues was considered; however, for the purposes of the Study these were considered to be responses to issues.

The Study also focuses on the *perspectives* of the different interested and responsible institutions. A perspective is the view of an issue taken by a particular institution or group of institutions, and in many cases different institutions have differing perspectives on the same issue. The 'nitrate issue' presents a good example. For the water regulators, the guardians of the water environment, nitrate is a threat to groundwater quality; for a water service company, nitrate involves investment in expensive treatment in order to ensure compliance with current or future quality standards; for water service customers, nitrate represents a perceived threat to health, as well as rising tariffs; for farmers, the nitrate issue implies changes to practices and possibly to livelihoods; for the environmental movement, artificially high nitrate loads may impact on wetland ecology; and so on. All of these 'institutions' have an interest in a better - and generally a common - understanding of the nitrate issue; several are funding research; few are coordinating their efforts or sharing their findings.

Stakeholders and consultation

A specific objective of the Study is to seek the views and participation of the main stakeholders, to the extent permitted by time and budgets. The stakeholders are all the parties who have responsibility for or interest in groundwater development, and thus have an interest in contributing to the identification of the primary issues affecting the management and sustainable use of groundwater and the definition of a national research agenda to address the issues. The stakeholders include bodies with diverse responsibilities, and consequently diverse perspectives, on the main issues and diverse interests in research. For example stakeholders include organisations with statutory regulatory duties, the water supply industry, water users - industry and agriculture, research organisations, professional associations and public interest groups.

Extensive consultation has been achieved through five devices: a 'mail shot,' individual consultation meetings, a UK Groundwater Forum, a science seminar, and national seminars held in England (for England and Wales) and Scotland (for Scotland and Northern Ireland). The *mail shot* set out to obtain a wide but relatively shallow sample of views and perspectives. This consisted of a simple checklist questionnaire, asking respondents to identify the groundwater issues of most concern to their organisation and, in addition, seeking information on current or recent R&D activities. Approximately 170 questionnaires were sent to a wide range of organisations and individuals with interests in groundwater development. The list, though not comprehensive, was a broad sample taken from NRA records of previous related consultations and their responses. Approximately 100 completed responses were received, many containing substantive written

BOX 1.2 UK Organisations Represented at the Initial Groundwater Forum Meeting (September 1994)

1. The Department of the Environment, Scottish Office Environment Department, and DoE (Northern Ireland), the government departments responsible for the water environment.
2. The Ministry of Agriculture, Fisheries and Food, responsible for agriculture.
3. The National Rivers Authority and the Scottish River Purification Boards, the statutory regulators of water quantity and quality in England, Wales and Scotland.
4. The Water Services Association, representing the PLCs which provide water and sewerage services, and the Water Companies Association, representing water supply only companies.
5. The Natural Environment Research Council, including the British Geological Survey (BGS), the national centre for geological research, survey and data.
6. The Foundation for Water Research, which promotes basic R&D of potential relevance to water and related environmental issues.
7. Local Government and the Institution of Waste Regulation Officers, representing their members.
8. Confederation of British Industries, representing its member companies, and two consulting firms (Mott Macdonald and Aspinwalls).
9. The Institute of Water and Environmental Management and the Geological Society, representing relevant professional and academic associations.
10. English Nature, representing environmental organisations.
11. The National Farmers Union, representing the interests of rural industry.
12. The University of Birmingham, representing academic institutions.

contributions in addition to the checklist. Details of responses as a function of organisation type and region are reviewed in Chapter 5.

Individual consultation meetings set out to obtain in-depth, but relatively narrow, views on the groundwater issues that were of most concern to organisations with legislative, regulatory or commercial interests in UK groundwaters. Several consultation meetings were held between NERC/ BGS project staff and representatives of the Department of the Environment, regional representatives of the NRA, and water service companies. The results of these consultation exercises are analysed in Chapter 5.

To capture the organisational perspectives of the principal stakeholder groups, a *UK Groundwater Forum* meeting was held at Keyworth on 15 September 1994. The purpose of the Forum was to provide a vehicle for the main parties with a major interest in UK groundwater to participate in a technical dialogue of current and future scientific issues in groundwater management in the UK. A mechanism was established at the Forum Meeting to review the progress and products of the Study. Forum meeting participants, and the constituencies that they represent, are listed in Box 1.2.

To enable the project team to establish rational scientific linkages between the issues arising from the consultation exercise and the R&D priorities, a *science seminar* was held at Wallingford on 20 January 1995. The seminar was attended by representatives from research organisations and universities with significant interests in UK groundwater research.

The mail shot asked whether respondents would be interested in attending a seminar on the results of the Study. Responses were almost universally positive, so two *national seminars* were held in February 1995. A seminar was held in Keyworth, Nottinghamshire, for England and Wales and a second was held in Perth, Scotland, for Scotland and Northern Ireland. The purpose of the seminars was to present the draft report and the findings of the Study, to seek broad consensus on issues, R&D needs and strategies, and to invite specific comment, for incorporation in the final report. Approximately 130 delegates attended the seminars, with representatives from national and local government, regulatory bodies, the water industry, water users and lobby groups.

Organisation and schedule

The Study was funded jointly by the National Rivers Authority, the Natural Environment Research Council, the Foundation for Water Research and the Water Services Association, as the primary representatives of the regulatory, the supply and the research and survey perspectives on groundwater development. At the start of the Study, a Steering Committee was established, comprising representatives of the funding organisations. Under the auspices and close guidance of the Steering Committee, the British Geological Survey (BGS) - a component body of NERC - undertook the Study. The Study schedule is shown in Box 1.3.

BOX 1.3 Strategic Study Schedule

Study commenced - July 1994.
Steering committee established, project goals and timetable defined, preliminary groundwater issues identified, draft report outline agreed

Individual consultations meetings - July to September 1994. Individual consultations held with regional representatives of the NRA, water service companies and with the DoE

Issues Papers drafted - August to October 1994.
Thirty-one issues papers drafted

Mail shot - August to September 1994.
Questionnaires sent to approximately 170 institutions and individuals with an interest in UK groundwater issues, 100 responses received

UK Groundwater Forum - September 1994.
UK Groundwater Forum meeting held

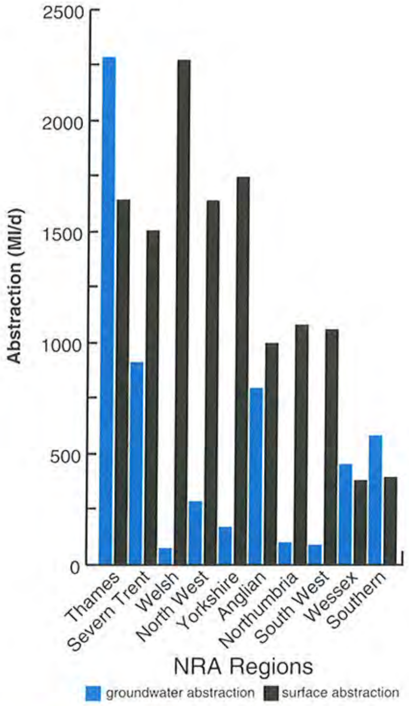
Review and report drafting - October to December 1994.
Consultations analysed, Issues Papers reviewed by Forum and edited, and first draft main report completed for review by steering committee

Report consultation and dissemination - January to March 1995. Science seminar held. Draft report completed, reviewed in two national seminars, and finalised for wide distribution

2. UK Groundwater

Groundwater use and importance

Groundwater provides about one-third of the water abstracted for public supplies in England and Wales, 11% in Northern Ireland and 3% in Scotland. In terms of overall water abstracted for all purposes, which is considerably greater than that abstracted for public supply and includes non-consumptive uses such as cooling, groundwater accounts for less than 15% of the total. This difference in use reflects the better quality of groundwater compared with surface water and thus its importance as a public supply source. The relative amounts of total groundwater and surface water abstracted in the NRA regions are shown in Figure 2.1. In contrast, Figure 2.2 shows the distribution of groundwater and surface water abstractions for public water supply by region. This figure illustrates the wide regional variation in the use of groundwater for public supply, with relatively minor use in some regions (for example Welsh, Northumbria, South West), while in others groundwater is a very important source of public supply (Thames, Severn-Trent, Anglian, Wessex and Southern).



The use of groundwater in different parts of the UK is shown in Figure 2.3. In most regions the greatest proportion is used for public water supply, and this is particularly true for central and south-east England. Industrial and agricultural purposes tend to dominate non-public supply use. It is generally recognised that local groundwater development is a least-cost option for meeting increasing water demand, at typically £0.1 to 0.5 million per Ml/d, a figure in line with demand management gains and direct river abstraction. However, in some cases the environmental costs may significantly alter the economics of groundwater development, if the impacts on baseflows and wetlands are considered.

Figure 2.2. Groundwater and surface water abstraction for public water supply for the year 1989/90

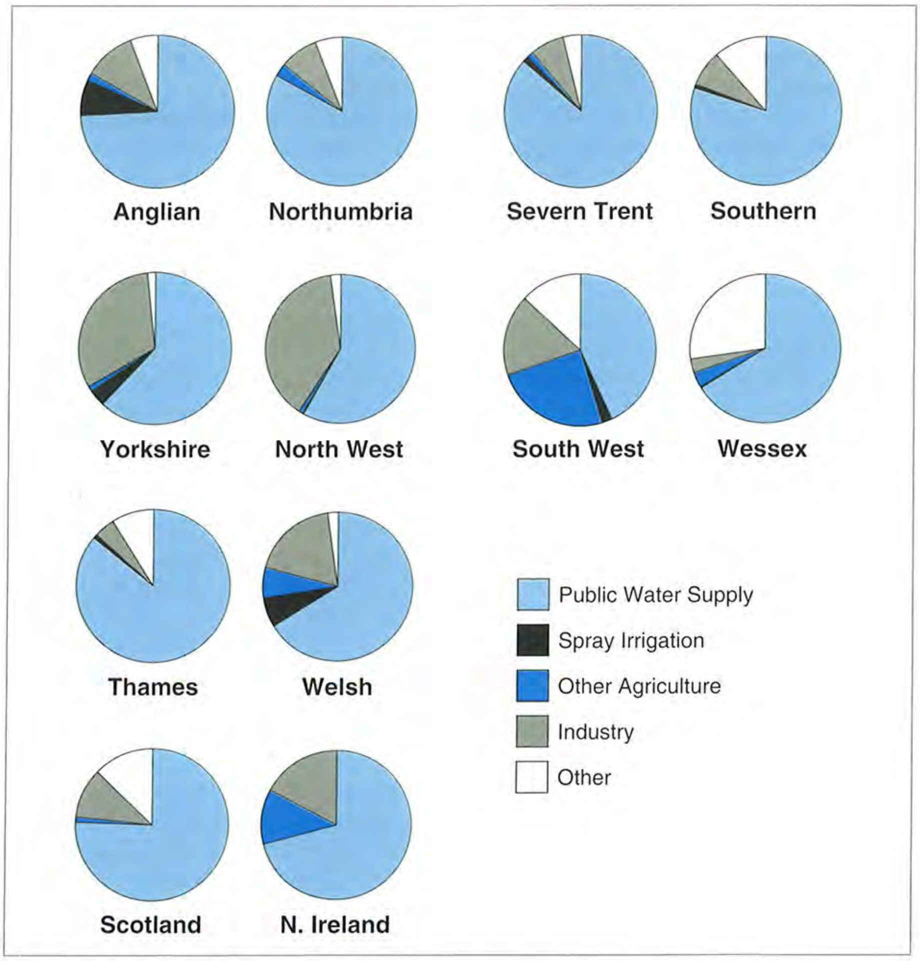


Figure 2.3 Illustration of regional variations in the use of groundwater

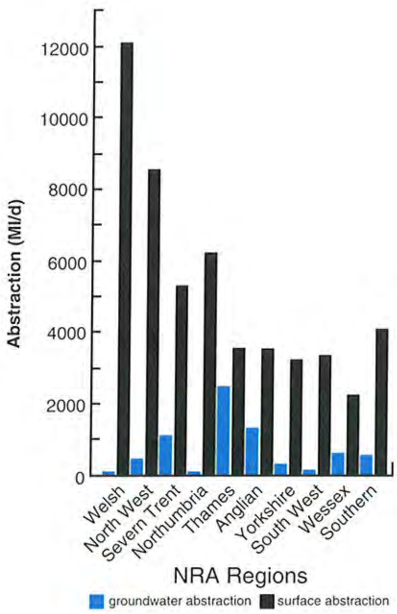


Figure 2.1. Total groundwater and surface water abstraction for the year 1989/90

Groundwater resources

The principal control on the occurrence of groundwater in the UK is the distribution of the relatively impermeable ancient (Pre-Cambrian and Palaeozoic) rocks to the north and the west, and the general restriction of the more permeable, younger (Mesozoic and Palaeogene) strata to the south and east of England. Thus, in broad terms, upland Britain or the regions to the north and west such as Northern Ireland, Scotland, Wales and Cornwall do not possess major groundwater resources of regional scale, although available groundwater resources are locally very important and they are often extensively used for private domestic water supplies.

Box 2.1 lists the aquifers occurring in the UK, with a rating of their importance. Figure 2.4 shows the location of the main aquifers in England and Wales, together with the significant aquifers in Scotland and Northern Ireland, although these do not offer such large groundwater resources as many aquifers in England. The principal aquifers of the UK lie in post-Carboniferous rocks and comprise the Chalk, the Middle Jurassic limestones, the Lower Cretaceous sandstones and the Permo-Triassic sandstones. Of these, the Chalk and Permo-Triassic sandstone aquifers are the most extensive, the Chalk underlying much of southeast England, and the Permo-Triassic aquifer outcropping extensively in the Midlands and northwest England. Figure 2.5 gives the outcrop areas of the aquifers in England and Wales.

The relative replenishment and abstraction of groundwater by aquifer in England and Wales is shown in Figure 2.6 (1977 data). The figure clearly shows the dominance of the Chalk and Permo-Triassic sandstones as groundwater sources. It also suggests that replenishment substantially exceeds use. Figures 2.7 and 2.8 show that in Scotland and Northern Ireland replenishment greatly exceeds abstraction for most aquifers, implying significant under-used potential.

However, the figures conceal the fact that not all replenishment is available for abstraction, as groundwater contributions to rivers must be maintained, and in some coastal regions

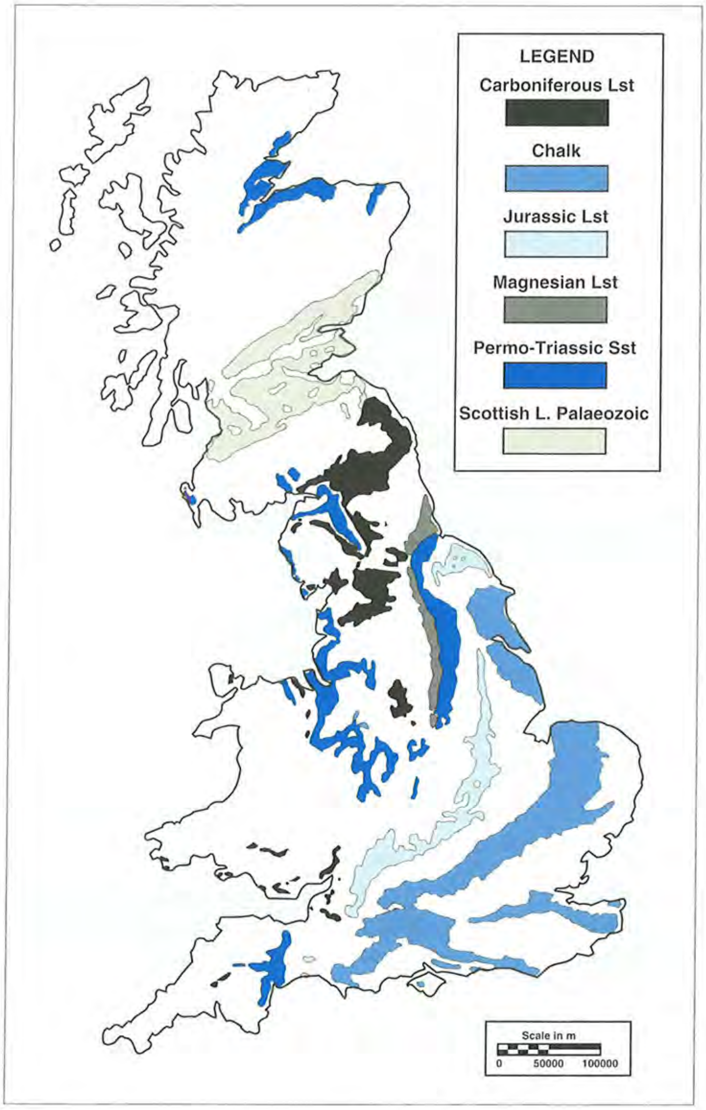


Figure 2.4a Principal aquifers of England, Wales and Scotland

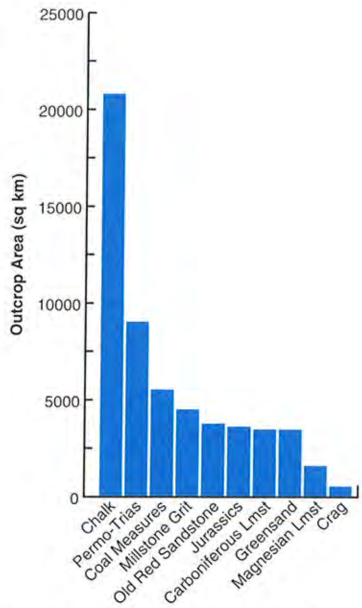


Figure 2.5 Outcrop areas of the English and Welsh aquifers

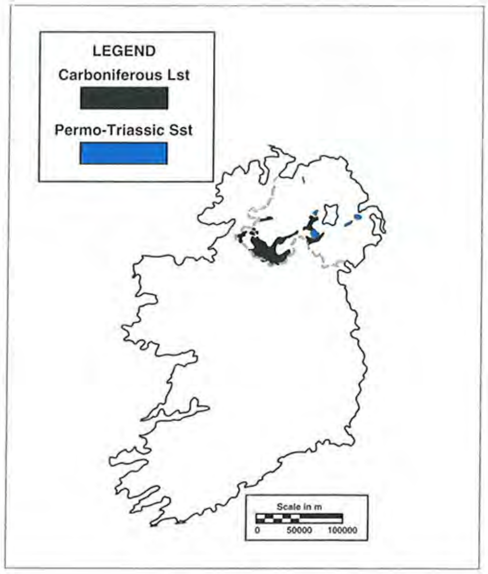


Figure 2.4b Distribution of aquifers in Northern Ireland

BOX 2.1 Aquifers in the United Kingdom (important aquifers in bold)

AQUIFER	LITHOLOGY	FLOW TYPE*	IMPORTANCE**
Superficial deposits	Thin & local alluvial deposits; thicker & more extensive glacial gravels.	I	●●
Crag	Sands (Quaternary), shelly sands (Pliocene).	I	●●
Eocene sands	Sands, clays, pebble beds.	I	●
Chalk	**Thick, soft, white microporous clastic limestone. Fractured in upper part.**	F	●●●●
Lower Greensand	**Variable sands & sandstones (commonly glauconitic) with clays & sandy limestones.**	I	●●●
Hastings Beds	Alternating sand-clay sequence. Sands, silts & clays.	M	●●
Spilsby Sandstone	Medium grained sands.	I	●●
Portland & Purbeck Beds	Limestones, shales, sandstones & evaporites	F	●
Corallian	Massive limestones & marls, limestones & calcareous sandstones in N England. Fractured.	F	●●●
Middle Jurassic limestones (Great & Inferior Oolites)	**S England - massive fractured oolitic limestones with clays & marls. Lincolnshire Inferior Oolite - Oolitic shelly limestones with calcareous sandstones & cementstones. Well fractured.**	F	●●●
Lower Jurassic sands (Bridport & Yeovil Sands)	Sands with variable clay.	I	●●
Marlstone Rock	Thin limestones & ironstones.	F	●
Permo-Triassic sandstones	**Thick layered heterogeneous sandstones & conglomerates, variably fractured.**	M	●●●●
Magnesian Limestone	**Massive dolomitic & reef limestones with marls, sandstones & breccias. Well fractured.**	F	●●●
Coal Measures	Thick fractured sandstones, alternating with mudstones & coals.	M	●●
Millstone Grit	Thick sandstones, grit, mudstones & shales. Variably fractured.	M	●●
Carboniferous Limestone	**Massive fractured karstic limestone**	F	●●●
Devonian Sandstone(Old Red Sandstone)	Sandstones, marls & (particularly in Scotland) conglomerates.	M/F	●●

* I - Intergranular flow
F - Fracture flow
M - Mixed flow

** ● Aquifer of relatively little importance
●● Aquifer providing useful local supplies
●●● Aquifer important locally
●●●● Aquifer of great national importance

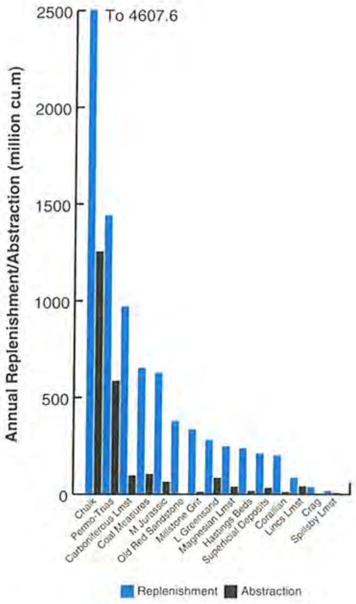


Figure 2.6 Replenishment and abstraction figures of groundwater by aquifer in England and Wales

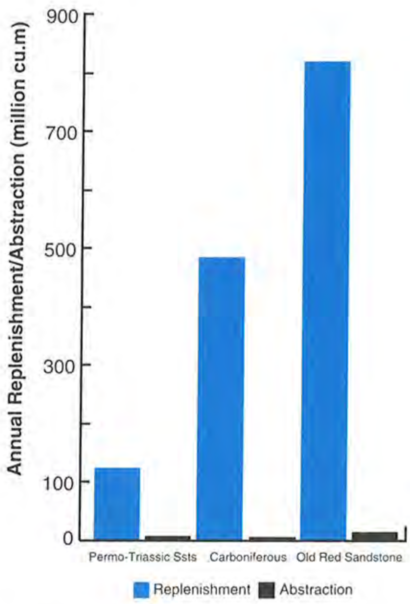


Figure 2.7 Replenishment and abstraction figures for Scotland

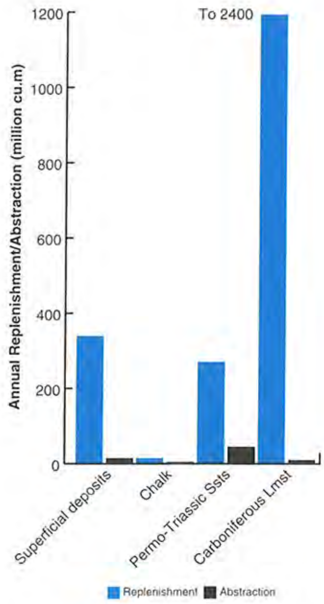


Figure 2.8 Replenishment and abstraction figures for Northern Ireland

Figure 2.9 Location of the 'top 40' low flows as identified by the NRA

seaward flow of groundwater must be permitted to prevent saline intrusion. In England and Wales, the NRA has drawn up a priority list of 40 locations where unacceptably low river flows are considered to be caused by excessive authorised abstractions, rather than drought. Within this list of the 'top 40', a 'top 20' schedule includes those locations requiring urgent attention. Figure 2.9 shows the location of the 'top 40' low flows. Following alleviating action, some of these locations no longer have serious low flow problems. In Scotland and Northern Ireland, groundwater abstraction licences are not currently required. Competition for resources is occurring in some aquifer units, notably the Sherwood Sandstone Group in the Belfast area and the Dumfries Permian basin. Only one case of derogation has yet been considered and that was resolved by recourse to the basic planning law.

Groundwater quality

Quality is a more complex variable in groundwaters than in surface waters. The relatively slow movement of water through the ground means that residence times are long, giving ample scope for interaction between the water and the material of the containing aquifer. As well as being more complex, quality is more difficult to assess in groundwater because of its relative inaccessibility.

The natural quality of the groundwater which is typically exploited from shallow aquifers is almost invariably good, with low concentrations of major ions throughout most of the aquifers of the country. There is typically an evolutionary process of cation exchange and oxygen removal down gradient (down-dip), as groundwater moves away from the recharge area. This eventually leads to reducing conditions deep in the confined zone of an aquifer, which can produce concentrations of metals which are problematic for groundwater supplies. Much of the groundwater put into supply in southern and eastern England is hard water from carbonate aquifers. The carbonate nature of these aquifers provides the buffering capacity which moderates the influence of acidic deposition, at least in the areas where groundwater is most heavily utilised. Acidic deposition is, therefore, only an important groundwater quality concern for some of the smaller, shallower aquifers of parts of upland Britain.

Most groundwater quality problems result from anthropogenic activity. The most important problems are a result of contamination by nitrate and pesticides, largely from agricultural activity, and trace organic compounds and other pollutants arising from urban and industrial development. Other groundwater quality issues, such as acid mine drainage and saline intrusion of coastal aquifers, may have significant impacts but these are typically of more restricted extent, affecting relatively small volumes of groundwater.

The most widespread, and probably the most well-documented, groundwater quality issue is that of nitrate. Since the mid-1970s, attention has focused on steadily rising groundwater nitrate concentrations in the areas of eastern and central England which receive the lowest rainfall and support the most intensive cereal cultivation. Although the rate of increase may have declined as a result of the agricultural measures introduced to lessen the risk of nitrate leaching, nevertheless significant areas of the Chalk, Lincolnshire Limestone and Sherwood Sandstone aquifers now contain groundwater with relatively high nitrate concentrations.

The NRA has recently assembled a large volume of historical nitrate data and, as a result, 72 such Nitrate Vulnerable Zones (NVZs) covering a total area of 650,000 hectares were proposed in 1994 for England and Wales. Nitrate is a less problematic quality consideration in Scotland and Northern Ireland because a combination of less intensive farming and significantly higher infiltration produces generally lower nitrate concentrations in groundwater. Nevertheless, there are two NVZs in Scotland and one anticipated in Northern Ireland.

Other groundwater quality issues have become apparent only more recently, as a combination of stricter legislation and improved analytical techniques allow trace organic compounds to be determined routinely. Recent research employing surveys of groundwater quality beneath several of our major cities has indicated the extent of contamination by trace organic compounds arising from current and, especially, past industrial activities. A wide range of compounds has been observed, and it can be anticipated that the legacy of past industrial development will be increasingly seen in groundwater, as it is in contaminated land. Today's contaminated land is tomorrow's groundwater pollution problem. The occurrence of industrial organic chemicals is not, however, restricted to the traditional urban and industrial heartlands of the country. Many users of such chemicals are located in rural areas; the most celebrated legal case involving industrial solvent pollution of groundwater involved a small leather-processing factory in a Cambridgeshire village.

The same considerations of tightening legislation and improved analytical techniques apply to pesticides. Hardly any knowledge of pesticide occurrence in groundwater existed before the mid-1980s, and some of the earliest results must be treated with caution because confirmatory determinations were not performed. Routine analysis of pesticides in groundwater at detection limits appropriate to assessing the situation with respect to a maximum admissable concentration (as specified in legislation) of 0.1 µg/l dates back only 3-4 years. Thus, the current situation is one of 'the more one looks, the more one finds'. While the current data do not provide an overall national picture, it is clear that low concentrations of pesticide residues, in the range 0.05 to 0.15 µg/l, do occur regularly in many groundwater sources. Concentrations of over 1 µg/l are, however, extremely rare.

It is also apparent from the existing data that the most commonly encountered compounds are the triazine herbicides, which have been widely used in non-agricultural situations as general weedkillers. Much less information exists for Scotland and Northern Ireland, although it can be anticipated that pesticides are likely to be less of a quality issue because of the dilution effect caused by relatively high effective rainfall. To date, hardly any information exists about the presence of pesticide metabolites, many of which may be as toxic and persistent as the parent compound.

Groundwater regulation

Although groundwater has been exploited in this country for millennia, it has been managed for less than 50 years. The legal instruments that have made this possible are summarised in Box 2.2.

The 1945 Water Act defined a regional water policy for England and Wales for the first time, instigating controls on groundwater abstraction in vulnerable areas by licensing and setting up a national archive of wells and boreholes. In order to operate a system of control on groundwater it was necessary to evaluate groundwater resources and their use on a regional and national basis, and thus an era of groundwater resource assessment began.

However, the 1945 Act did not recognise the often close relationship between groundwater and surface water, particularly rivers. With increasing aquifer development the effects on rivers, particularly in Chalk areas, became more marked. This caused problems because different organisations were responsible for aquifer development and river management. These difficulties led to the Water Resources Act of 1963, which was concerned with the management of the whole hydrological cycle, with river basins as the basic unit. The Act made

BOX 2.2 Main Legislation Affecting Groundwater in England and Wales

DATE	LEGISLATION	MAIN PURPOSE
1945	Water Act	National water policy defined, including some abstraction control and data collection.
1963	Water Resources Act	29 River Authorities formed to provide regional catchment-based integrated management of water resources; abstraction licensing introduced.
1973	Water Act	Ten Regional Water Authorities formed to provide complete regional management of water cycle.
1974	Control of Pollution Act	Created Waste Disposal Authorities to license disposal of solid wastes. Enabled Water Authorities to designate protection areas, and strengthened their power to prosecute.
1989	Water Act	Regional Water Authorities disbanded. Utility functions transferred to water service companies. National Rivers Authority formed as independent regulatory body. Activities of water companies to be overseen by Director General of Water Services.
1991	Water Resources Act; Water Industry Act; Land Drainage Act; Statutory Water Companies Act; Water Consolidation Act	Replaced and re-enacted the 1989 Water Act

it possible to manage the development of water resources, including groundwater, on a regional and national basis, and instigated an era of groundwater management. In particular the Act provided the basis for the development of aquifers in conjunction with surface waters, and investigations for several major river regulation schemes resulted.

A weakness of the 1963 Water Resources Act was that there was inadequate provision for the coordination of water resources development and water quality control (these two functions being controlled by separate organisations). This became problematic as the risks to groundwater from pollutants became increasingly recognised. Integrating quality and quantity was a significant advance in the 1973 Water Act. This Act substantially reorganised the water industry in England and Wales, reducing the number of operating units to ten multipurpose, self-financing Water Authorities with responsibility for managing the complete water cycle. Thus, water quality and quantity were made the responsibility of a single authority.

The increasing risk to groundwater sources from pollutants, from both diffuse and point sources, became the dominant issue in the 1970s. In 1974, the Control of Pollution Act increased the powers of Water Authorities with regard to pollution control and created waste disposal authorities. Between 1974 and 1989, increasing attention was given to the need to protect groundwater resources from pollution; however there was no coordinated national policy for aquifer protection, although several authorities did introduce protection policies. A policy has now been developed by the NRA for England and Wales.

With regard to groundwater development, the late 1970s and the 1980s saw a period of consolidation, following the major experimental programmes of the late 1960s and early 1970s. The Water Authorities were able to maintain supplies through the drought of 1976, and groundwater resources were not really seen as a major issue until the severe drought of the early 1990s.

The principal statutes in Northern Ireland and Scotland are respectively the Water Act (Northern Ireland) 1972, which empowers the Government of Northern Ireland with the responsibility for water conservation and pollution control, and the Water (Scotland) Act 1980. In addition the Water and Sewerage Services (Northern Ireland) Order 1973 places on the Government of Northern Ireland (effectively the Department of Environment for Northern Ireland) the sole authority for water and sewerage services. In Scotland the Regional Councils and Island Councils are vested with this same requirement, but the responsibility for water conservation and pollution control is held by the River Purification Boards and the Island Councils. However, there is currently no provision for abstraction licensing in either Northern Ireland or Scotland, although these are planned in the latter, using Control Orders.

A major new regulatory dimension was added through membership of the European Union. Directives adopted by the European Union normally impose a duty on the Member States to show compliance within a given time limit. However, a European Union Directive is not effective within a Member State until it is implemented by the Government of that State. This is achieved using the national systems of law and administration, resulting in new or amended Acts or Regulations.

Box 2.3 shows the European Council (EC) Directives which affect groundwater management. Generally, European Water Directives fall into two categories. The first defines acceptable water quality for particular

BOX 2.3 EC Directives Relevant to Groundwater

DIRECTIVE	MAIN PURPOSE
Directive 76/464/EEC Dangerous Substances to Water	To protect the aquatic environment from discharge of dangerous substances. Covered inland surface waters, estuaries, coastal waters and groundwater. Provided framework for control of 'Black' List I and 'Grey' List II substances.
Directive 80/68/EEC Groundwater	To protect groundwater against pollution caused by specified dangerous substances. Defined List I (most dangerous) and List II (other dangerous) substances. EC member states obliged to prevent list I and limit amounts of List II substances reaching groundwater.
Directive 80/778/EEC Quality of Water for Human Consumption	Defines quality standards (for some 60 substances) and monitoring requirements. Annex I sets out maximum permissible concentration and guide levels for 62 parameters and minimum required concentration levels for four parameters.
Directive 91/271/EEC Urban Waste Water Treatment	To encourage the reuse of water and the development of improved waste management. Lays down minimum requirements for treatment of urban waste water and disposal of sludge.
Directive 91/676/EEC Protection of Waters Against Pollution Caused by Nitrate from Agricultural Sources	To encourage agricultural practices which are environmentally beneficial, and in particular to reduce at source contamination by nitrate from agricultural practices. Restrictions placed on fertiliser use, maximum permissible nitrate level in drinking water set; zones vulnerable to nitrate pollution to be identified.

purposes (eg Directive 80/778/EEC). The second category relates to the quality of potentially polluting discharges, and includes Directives 76/464/EEC and 80/68/EEC. More recently the European Commission's Fourth Action Programme on the Environment introduced a new source-directed approach to pollution problems, and this has led to Directives 91/271/EEC and 91/676/EEC. Other Directives may relate to groundwater, but only indirectly; for example Directive 86/278/EEC (Use of Sewage Sludge in Agriculture) is aimed at protecting the environment from contamination resulting from uncontrolled applications of sewage sludge to agricultural land.

The current structure of the water industry and the form of the statutory responsibilities for the water environment in England and Wales are largely the result of the 1989 Water Act. This brought about the privatisation of the water industry in England and Wales and the setting up of the National Rivers Authority. Matters of national policy, and the ultimate responsibility for water functions and regulation, remain with the appropriate Minister (the Secretary of State for the Environment, the Minister of Agriculture, Fisheries and Food, or the Secretary of State for Wales). The NRA's statutory duties cover pollution control, water resources, flood defence, fisheries, recreation, conservation and navigation. These duties have been further strengthened by the 1991 Water Resources Act.

Much of the recent legislation, both national and European, relates to groundwater quality, now the dominant area of groundwater regulation. Routine monitoring of groundwater quality was established in the 1970s by the Regional Water Authorities. An informal network developed, largely in response to historical development of groundwater for potable use. There are, therefore, biases towards areas of concentrated population and water demand, and hence to the most productive parts of the most important aquifers. This distribution has positive aspects in relation to the detection of some human impacts on groundwater quality, but produced significant information gaps in some outcrop areas of the most important aquifers, and in the smaller aquifers away from the areas of highest groundwater use.

European and UK legislation now requires a range of organisations to assess groundwater quality. The surveillance of potability of public supplies, by which the Drinking Water Inspectorate evaluates compliance, provides a large body of data. These cannot, however, be used to provide a representative picture of the quality of groundwater in aquifers, as the samples are taken in the distribution system after treatment, storage and blending. The NRA has a responsibility "to monitor the extent of pollution in controlled waters", including groundwaters. Moreover, within the broad European context, there is an increasing need for member states to be able to provide a comprehensive national picture of the quality of groundwaters, as well as surface and coastal waters.

Controlled land use has become an important tool for achieving compliance with groundwater quality regulation, through groundwater resource and source protection. In 1992, the NRA published its Policy and Practice for the Protection of Groundwater and it is currently publishing a series of 1:100,000 maps of aquifer vulnerability. An aquifer vulnerability map has also been published for Northern Ireland (1994), and maps are also planned for Scotland, under the recently drafted Groundwater Protection Policy for Scotland.

BOX 2.4 General Aquifer Properties of Major UK Aquifers

AQUIFER	AVERAGE PERMEABILITY	POROSITY	DRAINABLE POROSITY	NOTES
Chalk	●●●●	●●●●	●	aquifer good in valleys, poor on hills
Lower Greensand	●●●	●●●●	●●●	
Jurassic limestones	●●●●	●●●	●●	permeability unpredictable
Permo-Triassic sandstones	●●●	●●●	●●●	
Magnesian Limestone	●●●	●●	●●	permeability very unpredictable
Carboniferous Limestone	●●●	●	●	permeability extremely unpredictable

●●●● very high ●●● high ●● medium ● low

The Chalk is the principal aquifer of the UK, with boreholes commonly yielding several Ml/d, sometimes exceeding 10 Ml/d from large-diameter wells, some with adit systems. The matrix of the Chalk is too fine-grained to possess a significant permeability; it is only an aquifer as a result of open water-bearing fractures. These fractures, and therefore the zones of high permeability, are not uniformly distributed throughout the Chalk, either with depth or geographically. Open fractures tend to be restricted to the upper few tens of metres, and therefore, although the Chalk may be several hundred metres thick in places, the productive thickness of the aquifer may be as little as 50 m. Also, there is considerable areal variability in transmissivity (permeability x aquifer thickness) with values varying over a few kilometres by an order of magnitude or more. These variations are thought to be associated with topography, with valleys often having higher values than interfluves. The porosity of the Chalk is generally very high, but the pore spaces are mostly too

Aquifer properties and their consequences

The relative importance of the issues affecting groundwater will vary greatly with hydrogeological environment and aquifer type. It is thus essential to identify the significant characteristics of the UK's main aquifers, before introducing the main issues that affect them. This section gives a broad overview of the relevant features of the main aquifers. Wherever possible, this is done in graphics and tables, using lay-man's terms and avoiding technical data, as few data would be misleadingly insufficient and sufficient data would be indigestible.

The behaviour of groundwater is to a large extent governed by the properties of the host aquifer. Box 2.4 shows the relative aquifer properties of the main aquifers in the United Kingdom. The *permeability* is a measure of the ability to transmit water (flow through unit area in unit time); *porosity* is the proportion of void space in the rock ; and *drainable porosity* is that part of the porosity that will drain (a function of pore connectivity and size).

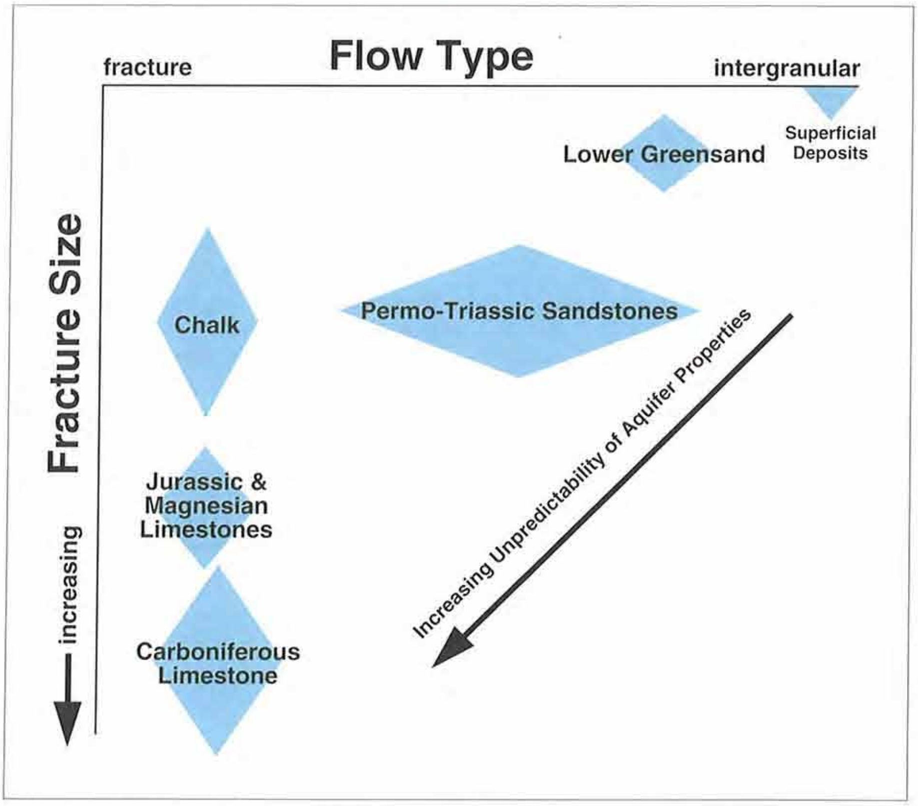


Figure 2.10 Flow characteristics of major UK aquifers

small to be involved with flow, and the drainable porosity of the aquifer is low. Atypically, the Chalk at outcrops in Northern Ireland is karstified with several large sinks and risings in the coastal area of County Antrim.

The aquifer properties of the Permo-Triassic sandstones are controlled by a combination of factors, including the lithology of the material (for example grain size and type), the degree of cementation, and the extent of fracturing. These factors, and therefore the properties of the aquifer are often both complex and varied, both laterally and with depth. In broad terms, however, the aquifer often has high permeability and high porosity, much of which is drainable. Well yields from the Permo-Triassic sandstones are variable, ranging up to 10 Ml/d in the Midlands, around 1 Ml/d in the north of England, Scotland and Northern Ireland, and less in the Cheshire Plain.

In the Middle Jurassic limestones, groundwater tends to move in discrete fractures and permeability is only meaningful for sufficiently large blocks of rock. This difficulty increases in the Permian Magnesian Limestone and in the Carboniferous Limestone, where most of the flow is in large discrete conduits. The porosities of these aquifers are generally small, and this can substantially affect borehole yields. In particular the Jurassic limestones drain rapidly and high yields are only found where the limestones are confined, where very high yields may be obtained. Yields from the Magnesian Limestone are dependent upon wells intersecting productive fractures, although several Ml/d are possible, and in the Carboniferous Limestone drilling is very speculative, with yields depending entirely on the size of fracture encountered.

The flow characteristics of the major aquifers are shown in a schematic way in Figure 2.10. Flow through fractures is a very important (and relatively little understood) characteristic of most of the aquifers in the UK and has profound consequences for the prediction of their behaviour, particularly with regard to groundwater transport processes. Figure 2.10 illustrates the point that while fracture flow is unimportant in minor unconsolidated aquifers, it is important to varying degrees in nearly all the major aquifers. Although fractures are generally of limited significance in the Lower Greensand, they can be very significant in the Permo-Triassic sandstones, and are fundamental to flow in the Chalk, Jurassic limestones and the Carboniferous Limestone. Figure 2.10 also illustrates in a general way fracture size for various aquifers. Thus a trend in the limestone aquifers is shown, ranging from the Chalk, where fractures are generally narrow (although there are many exceptions) through the Jurassic and Magnesian Limestones to the largely karstic Carboniferous Limestone, in which flow is predominantly in large conduits. By plotting the flow characteristics of the aquifers in this way a trend of increasing flow unpredictability can be shown, from matrix-dominated, relatively predictable aquifers such as unconsolidated sands, to the Carboniferous Limestone, where both paths of groundwater flow and borehole success are very uncertain.

If the properties of an ideal aquifer are well known it is possible by using simple models to predict groundwater flows in response to pumping. Thus, for example, protection zones, drawn as lines of constant travel time may be drawn around a pumping well. Figure 2.11 shows such generalised lines of constant travel time for a well pumping in different aquifers using simplified assumptions concerning the properties of the aquifers. Thus after a certain period of pumping, the model predicts that a particle will have reached the well from a much greater distance in the Chalk than in the Permo-Triassic sandstones. Other models based on generalised aquifer properties can be used to show that in an aquifer with high transmissivity and low storage such as the Chalk, pumping influences will spread much more rapidly than in an aquifer with high storage, such as an unfractured porous sandstone.

It must be recognised that reality is much more complex than can be portrayed by simple models. For example the shapes of constant travel time shown in Figure 2.11 rely on the aquifers being homogeneous, and this is not the case. In particular, the effect of fracturing in UK aquifers renders models subject to varying degrees of uncertainty.

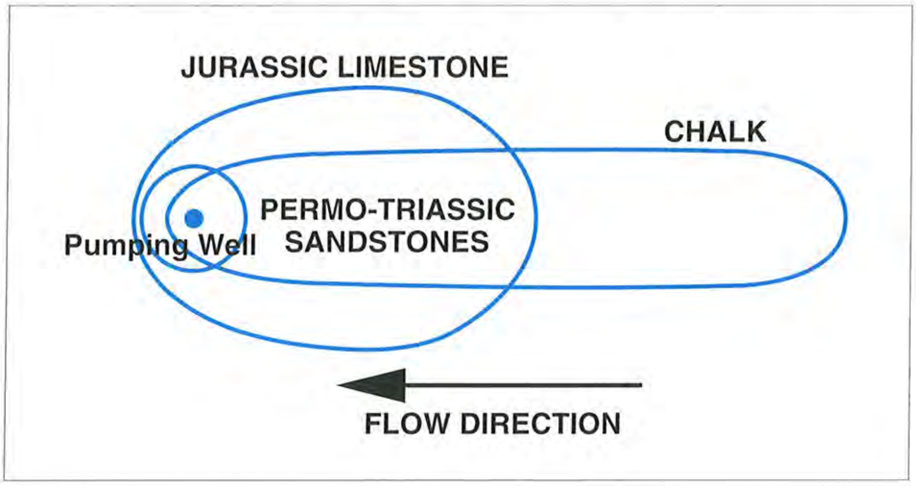


Figure 2.11 Generalised shape of Groundwater Protection Zones (of constant travel time) for various aquifers

3. Groundwater issues

Describing the issues

The groundwater resources of the UK have been described in the previous chapter. In this chapter, we briefly examine the *issues* affecting these groundwater resources. In Chapter 1, an issue was described as:

- a threat to groundwater quality or quantity;
- a constraint on groundwater development; or
- any significant uncertainty.

A critical component of this Study has been the identification and description of issues affecting groundwater resources, or likely to affect them into the foreseeable future. Following the identification of the issues, the underpinning scientific processes can be pinpointed and research needs prioritised. This is in marked contrast to identifying scientific challenges in the first instance and then seeking problems which the resolution of the challenges may solve.

The task of issues identification has been undertaken in an extensive process of consultation and review, involving many individuals and institutions. An initial list was drawn up by the Study team and then amended in a series of iterations following different consultation activities. Volume 2 of this Report, the UK Groundwater Issues Report, draws together these findings in a series of 'issues papers'. These papers together form a valuable reference volume and provide the background for this Report, giving essential detail on each of the issues.

Box 3.1 describes the format of the Issues Papers, which was standardised in order to ensure some consistency of approach. This provided a convenient structure for analysing the various aspects of each issue. There is, nevertheless, some latitude apparent, both in the identification of issues and in the application of a standard format to the individual issues papers; this latitude is an essential element of a study of this nature.

BOX 3.1 The Groundwater Issues Papers

The second volume of this Report, the UK Groundwater Issues Report, comprises 31 issues papers. Each issue paper has a similar structure. The **Problem Status** describes the present status of the 'problem'. **Related Issues** cross reference related issues. **Trends** identify the likely future changes in the problem - is it likely to get better or worse and what timescale is involved for any changes?. **Context Changes** highlight any important future developments that could substantially alter the status of the problem. This could include changes in demand or of land use, or recent or anticipated legislative or policy changes, for example. The **Learning Curve** section summarises the current state of knowledge about the issue and points out the key processes involved, identifying where we are on the learning curve. The **Perspectives** review the various points of view taken by different interested parties. **Benefits and Beneficiaries** identifies the main benefits of research in the topic area and who will benefit from this research. The **Response** summarises the recent response of interested parties to the problem, for example, in legislation or in a change of practice by the water industry. **R & D** captures the key research and development topics that would help to improve the understanding of the various issues that have been identified.

Box 3.2, over the next four pages, represents a summary of the 31 issues papers (themselves occupying almost 100 pages), distilling the Status, Trend, Learning Curve and Perspectives section of each issues paper as concisely as possible.

The issues are grouped into 14 'major' issues and 'other' issues. This priority rating is not justified until Chapter 6 of the Report. The order is nevertheless used in Box 3.2 to make the table of issues easier to use.

BOX 3.2 Summary of the Groundwater Issues

ISSUE	STATUS	TREND	LEARNING CURVE	PERSPECTIVE
		MAJOR ISSUES		
Acid mine drainage	Can lead to acidic and/or metal-rich discharges to surface waters and possible groundwater quality deterioration where an aquifer overlies an abandoned mine. Groundwater rebound can also mobilise pollutants from contaminated land and exacerbate land subsidence. Selective long-term pumping and other measures may be necessary.	Likely to become a serious problem in the UK as many metal mines and coalfields close down, and groundwater pumping stops. Rebound tends to be slow. It can take decades before the full impact is felt.	Underlying causes are well understood but difficult to quantify timing and extent of future problem without more research and monitoring. There are significant uncertainties in the hydrogeology and geochemistry.	Regulators, Utilities, Coal Authority, Fishing lobby, Insurance companies
Afforestation	Coniferous forests can increase evaporation considerably (leading to less water being available for groundwater recharge) but in the lowlands where the major aquifers are located, the effects, at least for broadleaf woodland, are relatively small and may even increase recharge slightly. Conversion of agricultural land to forest is likely to lead to a reduction in the use of fertilisers and pesticides and so may lead to an improvement in groundwater quality.	Tree planting programmes have led to a gradual increase in the percentage of UK afforested (but at 10%, still one of the lowest in Europe). Grants exist for more planting especially of broadleaves in the lowlands. Energy forestry may become more important.	Most studies of impacts of afforestation in the UK have been conducted on upland conifers. There are still significant unknowns about the water use of broadleaf trees and their impact on water quality, especially the effects of different tree species.	Regulators, Utilities, Forestry Authority
Contaminated land	Land contaminated by past industrial activities has left a legacy of potentially toxic substances including tars and oils, heavy metals, other organics and soluble salts. Where contaminated sites overlie aquifers, they often eventually lead to serious local pollution of underlying groundwater, especially when sites are disturbed during redevelopment.	Tighter controls of industrial emissions mean that future contamination of land should be less than in the past. However, the historical legacy is large and will remain.	Most groundwater clean-up has been pioneered in the US, and the limited UK experience is not in the public domain. The effectiveness of technologies under UK hydrogeological conditions has not been proven due to inadequate monitoring.	Regulators/HMIP, DoE, Industry, Local Authorities Utilities, Private GW users
Landfill	Landfill leachate is potentially highly contaminating to groundwater. Although modern landfills are constructed with engineered liners (which are designed to limit leakage to an acceptable rate) many old landfills exist which have no such liners and are a potential source of pollutants to aquifers.	Statutory minimum monitoring requirements for landfills were introduced in 1994. QA/QC procedures are being introduced both for liner construction and monitoring protocols.	Much is known about the chemical processes that take place in landfills, but there is a need for better techniques for monitoring groundwater contamination, and more systematic review of existing monitoring data. The area to which research can contribute the most is to assist regulatory bodies to determine acceptable leakage rates on a site-specific basis.	Waste Regulation Authorities, Regulators, DoE, Industry
Land-use change	Land-use changes occur slowly but may result in significant long-term impacts on water resources, both in quantity and quality. Important changes that may occur are: the introduction of groundwater protection zones, reductions in fertiliser and pesticide usage; changes in afforestation and deforestation, and the spread of urbanisation.	Changes in the use of agricultural land will reflect the Common Agricultural Policy and groundwater protection policies. There could be significantly more forestry in the lowlands and a continuing slow loss of land to urban development.	Although there have been many detailed studies of the hydrological influences of various aspects of land use change, there is a need to be able to extend this knowledge to larger areas, eg the catchment scale.	Regulators, MAFF, DoE, Conservation bodies, Planners
Low flows	Groundwater is an important source of baseflow to many rivers. There has been increasing concern with low flows in some lowland Chalk and P-T Sandstone streams. This has led to several conjunctive use schemes in which pumped groundwater is used to supplement streamflow during periods of low flow.	There are no indications yet that there are significant trends in the natural variability of low flows but there have been a significant number of dry winters in the last 20 years.	The broad processes are well known but there are serious limitations in the application of general models to particular sites, and there is a need for some well instrumented and monitored catchments.	Regulators, Utilities, Farmers, Conservation bodies
Nitrate	There is extensive pollution of the unconfined parts of the major UK aquifers. In many boreholes concentrations are at, or approaching, the maximum permissible concentration for drinking water. Treatment or blending is often required. In extreme cases, boreholes have been closed down completely.	Nitrate might take 5-50 yrs to reach the water table. Nitrate concentrations in groundwater have been rising steadily in many areas. This trend is likely to continue in the short term, although locally there is some levelling off. However, changes in cropping practice, reduction in fertiliser use and the introduction of NSAs and NVZs should reduce the problem in the long term.	A large amount of research and monitoring has been undertaken, and the key processes have all been identified. Improved understanding of natural *in-situ* denitrification, the effectiveness of land-use change in reducing nitrate leaching and the significance of preferential flows in the unsaturated zone are still required.	Utilities, Regulators, MAFF, Conservation bodies

BOX 3.2 Summary of the Groundwater Issues (continued)

ISSUE	STATUS	TREND	LEARNING CURVE	PERSPECTIVE
		MAJOR ISSUES (continued)		
Non-aqueous phase liquids (NAPLs)	Non-aqueous phase liquids, both those denser than water (DNAPLs) and those lighter than water (LNAPLs), have been, and remain, in very wide-spread industrial use and are insidious groundwater pollutants. Small amounts of solvent can contaminate large volumes of groundwater and NAPLs are a major component of the contaminated land problem.	DNAPLs give rise to greater concern than LNAPLs. Groundwater beneath industrial sites and airfields is especially likely to be contaminated but DNAPL contamination also appears to be widespread in aquifers situated beneath major cities.	The behaviour of LNAPLs is reasonably well understood although more closely-monitored experience of the evolution of pollution/remediation incidents is needed. It is still difficult to predict the fate and migration of DNAPLs in UK aquifers, and further detailed research and monitoring is required.	Industry, Regulators, Utilities
Pesticides	Pesticides are widely used both by agriculture, industry and public authorities. There is the danger that some residual pesticide may find its way into groundwater. The maximum admissible concentration of any pesticide in drinking water is currently set at the very low level of 0.1 µg/l. Groundwaters are well protected compared with surface waters but some pesticides, especially the triazine herbicides, mainly of non-agricultural origin, have already been detected in groundwaters.	Increasingly sensitive analytical methods mean that confirmed detections of pesticides in groundwater are increasing. There is no systematic national survey to detect trends. The use of less persistent pesticides and lower concentrations means that the problem should eventually diminish.	Limited research on the occurrence of pesticides in UK groundwaters. Preferential flow, including through soakaways, may be important for rapid transmission to water table. Rate of degradation in aquifers likely to be slow but parameters unknown.	Utilities, Regulators, Chemical industry
Remediation	A wide variety of organic and inorganic contaminants can be found in groundwater especially at former industrial areas. Remediation aims to clean up a site or aquifer sufficiently to be fit for its new use. The most persistent pollutants are often present as discrete phases (eg NAPLs) or are strongly adsorbed to the solid phase. Available technologies include pump-and-treat, gas venting and *in situ* bioremediation.	Although some aquifer remediation is taking place in the UK, it does not approach the scale of North American activity. The 'polluter pays' principle adopted in the UK has been largely ineffective due to difficulties in identifying the polluter and in subsequently proving liability.	Much of the extensive experience of remediation gained overseas will not be relevant to UK aquifers, especially dual porosity aquifers. There is little documentation of UK work. Restoration of all contaminated groundwaters to drinking water quality is impractical.	Regulators, Industry, Utilities
Source protection	In 1992, the NRA published their national groundwater protection policy. This aims to protect groundwater sources and to provide guidance to planning and waste disposal authorities on the siting of potentially polluting activities. The definition of NSAs and NVZs is closely related to that of source protection zones.	Source protection zones for at least 800 groundwater abstractions (wells and springs) have been defined by computer models.	The attempt to define source protection zones for all major groundwater abstractions has increased awareness of the issues involved and led to a greater scrutiny of the methods used.	Regulators, Local planners, Waste Regulation Authorities, MAFF
Sustainable yield	Groundwater must be managed as a sustainable resource and abstraction must be balanced against recharge. In a few areas of the UK, groundwater abstractions exceed the sustainable yield and this has resulted in a reduction in baseflow to streams, contraction of wetlands or increased saline intrusion.	Requests for groundwater abstraction licences are no longer being granted in areas where increased abstraction cannot be sustained. Some existing licences are set too high but cannot be changed without compensation.	Various methods of recharge estimation and therefore sustainable yield are currently being reviewed by the NRA in order to arrive at a consistent national approach; there remains considerable uncertainty in aquifer storage parameters and groundwater surface water relations.	Regulators, Utilities, Farmers, Industry
Vulnerability	Vulnerability is the degree of access of an aquifer's saturated zone to the vertical penetration of pollutants from the land surface. There is currently a concerted effort to map aquifer vulnerability specifically in relation to nitrate. A challenge is to combine sparse data on aquifer properties with critical characteristics of the pollutant of interest to produce meaningful vulnerability maps at a useful scale.	Vulnerability depends on many factors including the contaminant of interest, the type and depth of soil, the amount of recharge and the physical, chemical and biological properties of the aquifer. There is likely to be an increasing interest in quantitative measures of vulnerability.	Vulnerability to nitrate is of greatest concern at present but vulnerability to DNAPL pollution and acidification have also been considered. Pesticides and microorganisms also need to be considered. Preferential flow is often a critical factor.	Regulators, Utilities, MAFF, Farmers
Wetland conservation	Many of the remaining UK wetlands are now protected by designation as SSSIs etc. Planning applications frequently require a scientific judgement about the impact of a particular development on a wetland. The local hydrogeology is usually inadequately understood to assess the impacts realistically.	The threat from agricultural drainage is receding. Groundwater abstraction is a major threat which is now generally tightly controlled.	The maintenance of the proper groundwater level is obviously critical for wetlands. It is therefore important to know the extent of local and regional groundwater flows as well as the influence of any abstractions.	Regulators, Developers, Foresters

BOX 3.2 Summary of the Groundwater Issues (continued)

ISSUE	STATUS	TREND	LEARNING CURVE	PERSPECTIVE
		OTHER ISSUES		
Acidification	Acidic deposition from the atmosphere is widespread in the UK, but most major aquifers are well-buffered and unlikely to be adversely affected. In some cases it can lead to decreased alkalinity of baseflow to rivers, mobilisation of aluminium and increased corrosion of underground pipes.	Changes in groundwater are slow and tend to occur over decades. Although there has been a steady reduction in emissions of SO_2 since the early 1970s, NO_x emissions have increased.	The extent and trends in surface and groundwater acidification in the UK are now quite well established.	Utilities, Regulators
Borehole efficiency and rehabilitation	It is important that supply and observation boreholes are maintained in efficient working order.	The recent Asset Management Plans prepared by the Water Industry have focused attention on the condition of all of their boreholes.	Some of the processes which affect borehole performance are not yet well understood.	Utilities, Regulators
Climate change: effects of	The impact of climate change on water resources will be complex due to numerous interactions between climate, demands and resources. Not yet clear whether there will be a change in groundwater recharge, as precipitation changes are generally poorly modelled.	Scenarios suggest warmer summers and especially winters and a 5-8% increase in winter rain by 2030. A sea level rise of 20 cm is expected but impact on saline intrusion in coastal aquifers should be small.	Scenarios indicate global warming over the next 50 years but the extent of this will depend on future greenhouse gas emissions. The hydrogeological consequences for UK groundwater are not yet clear.	Utilities, Regulators, Agriculture Conservation bodies
Deep waste disposal	Discharge of toxic liquid waste to underground strata through wells, shafts or boreholes was widespread in the UK. Adverse effects could include groundwater pollution, ground instability and gaseous emissions.	Stricter planning controls in recent years have reduced the number of discharges. Currently some interest in storing supercritical CO_2 underground.	Most of the information about deep well disposal of wastes is based on experience in the USA.	Regulators, DoE, Local Authorities and Waste Regulation Authorities
Geochemical baseline change	Several elements (eg Mn, Fe, F, As) occur naturally in groundwaters at concentrations which may be at or close to statutory limits. Fluoride is also sometimes lower than desired.	The increase in chloride and nitrate in groundwaters often reflects increasing contamination. There are insufficient data to detect changes in most minor elements.	Important geochemical changes can occur along groundwater flowlines as the waters 'age'. The concentrations of many minor elements have been measured in the UK's major aquifers.	Regulators, Utilities
Heavy metals	Most heavy metals such as cadmium, lead and mercury, are toxic and act as cumulative poisons. High concentrations should not normally be a problem in the major UK aquifers since these aquifers are well buffered at or near neutral pH where most heavy metals are quite immobile. More mobile anionic species, such as arsenic, do give local problems. Most lead in drinking water comes from the distribution system.	Occasional, high concentrations of trace metals are found in groundwaters from most UK aquifers. Acidic, shallow aquifers are most susceptible. There has been considerable interest in the fate of heavy metals applied to land in sewage sludge but this relates mainly to soil protection.	Heavy metals have been most widely studied at contaminated sites and in soils where metal-contaminated sewage sludge has been applied. Some trace metal data are available for most UK groundwaters but the database is selective and far from complete.	DoE, Utilities, Regulators, MAFF
Microbiological contamination	Contamination of groundwater with pathogenic organisms (eg *Cryptosporidium)* is rare but not unknown in British aquifers. *Cryptosporidium* does not respond to the normal chlorination process, but can be removed by slow sand filtration.	Recent work has been stimulated by the occasional detection of groundwater contaminated with pathogenic organisms.	Subsurface microbiology is a new discipline. There is interest in the transport and survival time of micro-organisms in aquifers. Measuring their *in situ* activity is also a key issue.	Consultants, Utilities, DoE
Quarrying	Quarrying often interferes with local hydrogeology since it can permanently affect groundwater flowpaths, including flow to springs. During extraction there may be pumping and a temporary reduction in the water table while later abandoned quarries fill with water and change the groundwater regime permanently.	There is a general tendency for fewer, but deeper (sub-water table), quarries, which will impact on groundwater more than shallow quarries.	It is only since 1988, when Environmental Impact Assessments became necessary, that the impact of quarrying on the environment has been formally assessed, although there have been detailed studies since the 1960s.	Regulators, Aggregates Industry, Private GW Users, Environmental lobby, Utilities
Radioactive waste disposal	Three types of waste: low-level waste, LLW (protective clothing etc); intermediate-level waste, ILW (fuel cladding etc) and high-level waste, HLW (from reprocessing nuclear fuel). HLW contains 95% of total radioactivity. LLW largely landfilled; UK Nirex plan to build an ILW repository at Sellafield; HLW will be stored at surface until it becomes ILW. All pose a potential risk to groundwater.	Small amounts of LLW are disposed of in numerous landfills as well as at Drigg near Sellafield and at Dounreay. Since the radioactivity decays very slowly, this problem will be around for a long time. Protecting the groundwater is a major consideration.	There have been extensive studies of potential leakage of radioactivity at Drigg and at potential ILW sites. Understanding past flow is often the key to predicting future flows. The hydrogeology is a critical part of the safety case.	UK Nirex, EU
Radon, radium and uranium in groundwater	Radon, radium and uranium are naturally-occurring radionuclides that are concentrated in certain types of rock such as granite. They move dissolved in groundwater. Radon is a gas and there has been concern that exposure to high concentrations of radon in houses may be a health hazard. Direct intake in drinking water is not believed to be a problem.	Since these radioactive substances are naturally-occurring there is no reason to believe that the situation is getting worse. Increased ventilation should reduce the radon problem.	Most studies of the health effects of these substances have been carried out in the USA. Radon exposure is the most serious of these risks in the UK and is associated with lung cancer. Radium and uranium may also cause bone cancer.	NRPB, UK Nirex, Local Authorities DoE

BOX 3.2 Summary of the Groundwater Issues (continued)

ISSUE	STATUS	TREND	LEARNING CURVE	PERSPECTIVE
OTHER ISSUES (continued)				
Rising water levels	Groundwater levels beneath many of the UK's major cities (London, Liverpool, Manchester, Nottingham) declined during the period of industrial growth but are now rising again and could eventually reach higher levels than preurbanisation. This creates problems for underground structures such as tunnels and sewers. There is also a potential for accelerated groundwater contamination if contaminated land become saturated.	Groundwater levels in many urban areas have risen by about 0.3 to 2 m/a since the 1950s. Future changes depend on many factors. This water has not yet been exploited by the Water Utilities because of quality problems.	The rate of groundwater level rise has been closely monitored in many locations. It is difficult to estimate recharge (including mains leakage) in urban areas which makes modelling difficult.	Regulators, Utilities, Industry, Landfill operators
Saline intrusion	Saline intrusion is the landward movement of the saline interface where coastal aquifers discharge to the sea or tidal estuaries. The position of the freshwater-saline water interface varies with seasonal changes in water level, hydraulic gradient and abstraction. If abstraction is excessive, freshwater boreholes can become saline and unusable. Reversal is slow and difficult.	Changes in saline intrusion are continuous and long term. Active saline intrusion due to pumping is most important for aquifers on the south and east coasts. Global warming and the rise in sea level may slightly increase the problem (see also Climate change).	The basic theory is well understood and current models are quite effective for homogeneous aquifers on a regional scale. In practice, predictions are often poor and borehole observations may not adequately reflect changes in the aquifer.	Utilities, Regulators
Sewers, soakaways and septic tanks	Leaking sewers may give rise to the bacteriological contamination of private, non-chlorinated groundwater sources and to public supplies where chlorination has broken down, as well as to the general degradation of urban groundwater quality. Septic tanks may be significant sources of rural groundwater pollution and soakaways (eg from roads) provide potential rapid paths for pollutants to reach the water table.	About one major incident per year occurs of sewage-related groundwater contamination in England & Wales. Deterioration of old, frequently Victorian, sewers means that sewage leakage is likely to increase. Modern sewers are better. There is now greater awareness of the potential dangers from soakaways.	A CIRIA-funded study is being concluded which has examined the occurrence, nature and cause of sewage-related groundwater contamination in England & Wales. Bacteria, nitrate, phosphate and boron are the best indicators of sewage contamination. Key processes in sewer failure are poorly understood.	Industry, Regulators, Dept of Transport
Sludge utilisation	Various forms of farm waste (slurry, farmyard manure, etc) are applied to land in areas where animal rearing is practised. A large proportion of UK sewage sludge is also applied to land. The impact of these organic-rich residues on groundwater will probably depend on the extent of nitrate leaching and, in the case of sewage sludge, on the possible leaching of persistent trace organics. In addition, there is an increasing use of landspreading as a cheap industrial waste disposal option.	There is likely to be an increased application of sewage sludge to land especially after the cessation of dumping of sludge to sea by Dec 1998. The amount and timing of applications of all types of organic waste will be controlled in NVZs.	The amounts and composition of the organic-rich wastes produced are understood. Need a better understanding of their rate of breakdown and nitrogen release. Do not know much about the fate of trace organics from sewage sludges but evidence to date suggests that they will not be a serious problem.	Utilities, Regulators, DoE, MAFF, NRA, Local Authorities
Subsurface methane	Landfills and agriculture are the principal sources of methane emission to the atmosphere. Methane is a potent greenhouse gas whose concentration is increasing. Methane is also present naturally in groundwaters from certain organic-rich strata. The migration of methane-rich groundwater can lead to potentially dangerous accumulations of methane in restricted air-spaces.	The future emissions of methane in the UK will largely depend on the mass of material landfilled, its composition and the management of the landfill. Other geological sources are likely to remain constant.	Very little is known about the methane content of most groundwaters. Methane from the atmosphere is normally oxidized in the soil but may occasionally also be produced in groundwaters.	Construction industry, DoE, Waste Regulation Authorities
Unregulated rural supplies	There are at least 50,000 small private sources in England and Wales and a further 38,000 in Scotland. These are mostly groundwater sources - typically boreholes, wells or springs. These sources are concentrated in the rural and upland areas, often in 'hard rock' areas. The sources are often quite shallow and therefore relatively susceptible to pollution.	The use of small private sources is increasing in most parts of the UK. There is a parallel increase in private effluent disposal leading to increasing risk of groundwater contamination from septic tank effluent.	Generally the hydrogeology of areas where small private supplies dominate is poorly understood. In hard rock areas, fissure flow tends to dominate giving short flow paths with a greater potential for contamination by pathogenic bacteria and nitrate.	Environmental Health Officers, DoE, Regulators
Wastewater reuse	Cities produce large quantities of wastewater which is potentially available for reuse. There is some scope in the UK for the use of partially-treated wastewater for artificial recharge of aquifers.	The most comprehensive UK experience of recharge with partially-treated wastewater was in the Chalk of southern England. This has been discontinued but reuse could well increase in the future.	Most experience is from arid and semi-arid areas. Depending on the degree of treatment, the greatest danger in using partially-treated water arises from cysts, viruses and persistent organics.	Utilities, Regulators, Industry

4. Consultation: national and regional findings

The mail shot: a national overview

There were approximately 100 respondents to the mail shot (sent to 170 addressees) requesting that the addressees annotate a list of groundwater issues, ticking those issues of concern to them, and giving two ticks to those issues which concerned them most. The mail shot was sent to an unsorted sample of addressees drawn from NRA records of previous consultations.

Respondents were classified by organisation type and by region. Over a third of the respondents were classified as national, due to the nature of their activity or responsibility. The profile of the mail shot respondents is shown in Box 4.1, and, although not at all evenly distributed organisationally or regionally, the sample is broadly based. A bias that became apparent is the relatively large number of local government respondents and the absence of NRA respondents (as the latter were the subject of individual consultation meetings).

BOX 4.1 Mail Shot Respondents

ORGANISATION TYPE	NO.
National government	7
Local government	18
Regulators	12
Water industry	16
Environmt. NGOs	7
Consultants	18
Academia	10
Users/Industry	10

REGION	NO.
National	41
Anglian	3
Northern Ireland	2
North West	2
Scotland	10
Southern	11
Severn Trent	13
South West	6
Thames	8
Wales	3
Yorkshire	4

The mail shot results represent an interesting and valuable dataset, stored in a relational database, which allows organisational and regional comparisons. As a general rule, relative ratings given below were derived by scoring one point for a single tick and two for a double tick. However, the numbers are insufficient to permit valid statistical analysis and the interpretation of the results that follows in the ensuing paragraphs is presented with the caveat that it demands the accompanying subjective analysis, which draws on the other consultation 'instruments' employed. Nevertheless, the mail shot was a serious attempt to go beyond the conventional involvement of key players and revealed many interesting perspectives. In many cases, the simple checklist sent out was returned with a detailed list of concerns and research priorities.

Box 4.2 shows the overall priorities resulting from the mail shot, listing the top 16 issues, in order of overall score, across the full mail shot sample; the first seven issues were rated particularly highly. It is clear that this mixed list includes issues of interest to different types of institutions; given the wide range of organisations and regions, Box 4.2 represents no more than a mixed menu of everybody's concerns.

Regional perspectives

The high priority issues listed above are priorities in all regions. Regional differences did emerge, however, particularly between areas that could be classified as 'upland' and 'lowland' parts of the UK. Upland areas include most of Scotland, Wales, Northern Ireland and South West England, with parts of other areas of England, and lowland areas include central, southern and eastern England, with parts of other areas. Box 4.3 lists some issues that emerged as being of particular importance in upland UK. The problem of unregulated rural supplies is clearly of great potential importance, with perhaps half a million people drawing water supplies from about 90,000 sources. This is discussed further in the appropriate issues paper.

BOX 4.2 Overall Priority Issues from Mail Shot

Landfill	●●
Contaminated land	●●
Source protection	●●
Nitrate	●●
Pesticides	●●
Low flows	●●
Vulnerability	●●
Acid mine drainage	●
Reliable yield	●
Remediation	●
Land-use change	●
Sludge utilisation	●
Heavy metals	●
Climate change	●
Sewers etc	●
Wetlands	●

●● high priority ● priority

BOX 4.3 Key Groundwater Issues in Upland UK

- impacts of water-level rebound in abandoned mines
- impacts of quarrying below water table
- impacts of contaminated land on groundwater
- impacts of sewage sludge application
- unmanaged groundwater resources: limited resource assessment, unlicensed abstraction (Scotland and Wales), no protection
- diffuse agricultural pollution, including sheep dip disposal, of shallow groundwater
- various risks with many private water supplies from minor, shallow aquifers

In lowland UK, where groundwater is generally extensively developed and managed, the issues take on a different flavour. The tensions between environmental protection, growing demand for water and tight controls on water tariffs all compete, requiring an increasingly refined understanding of the environmental and economic impacts of groundwater abstraction.

Some of the key issues in lowland UK are listed in Box 4.4; these are generic issues, irrespective of the perspective of any particular agency. However, it is in lowland UK where the perspectives of different agents become more defined and different, reflecting the various constituencies and their interests. This is the subject of the next chapter.

BOX 4.4 Key Groundwater Issues in Lowland UK

- environmental impact of groundwater abstraction
- effectiveness of abstraction controls on baseflows
- effectiveness of nitrate application controls
- effectiveness of source protection zones
- prediction of groundwater behaviour in drought
- extent and persistence of pesticide contamination

5. Institutional perspectives

Introduction

Many different institutions have an interest in groundwater resources; evidence of the extent of this interest was shown by the scale and breadth of the response to the consultation exercise. Figure 5.1 illustrates the diversity of institutions within the institutional framework and is largely self explanatory. This Chapter seeks to examine the perspectives of different institutions regarding groundwater issues, drawing on the mail shot, the consultation meetings and the UK Groundwater Forum inputs.

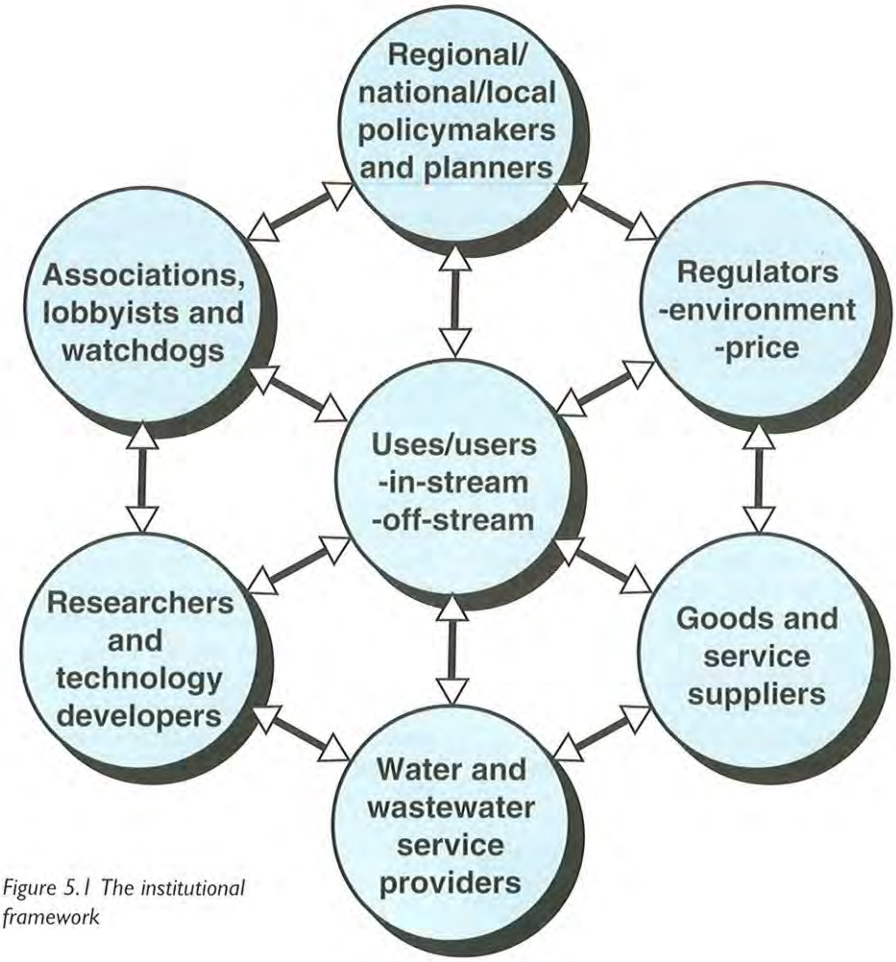


Figure 5.1 The institutional framework

Central Government perspectives

Central Government is responsible for national water policy and has ultimate responsibility for water regulations and functions, through the appropriate Minister: the Secretary of State for the Environment; the Minister for Agriculture, Fisheries and Food; the Secretary of State for Scotland; the Secretary of State for Northern Ireland; or the Secretary of State for Wales.

The current statutory responsibilities for the water environment and structure of the water industry were largely defined in England and Wales by the Water Act 1989. This Act effected the privatisation of the water and wastewater service industry, overseen by the Director General of Water Services, and the setting up of an independent regulator, the NRA. In taking over the management of the water environment, the NRA also assumed responsibility for most of the water R&D programme in England and Wales, formerly managed by government departments, including almost all directly groundwater-related research. However, divisions of DoE and MAFF are responsible for related policy areas, such as contaminated land, landfill, industrial and agricultural pollution and pesticide regulation, and maintain associated R&D programmes.

Central Government is responsible for ensuring the development of appropriate and relevant EC directives on the protection and management of water, including groundwater, through, for example, the analysis of threats from pollution, and of benefits (eg ecotoxicological and environmental) and economic and social costs of protection. Once adopted by EC legislation, Government is responsible for compliance with duties imposed on Member States by EC Directives - such as 91/676/EEC (Nitrate Directive), 80/778/EEC (Drinking Water Directive) and 80/68/EEC (Groundwater Directive) - through their integration into national legislation.

The Drinking Water Inspectorate (DWI) of DoE, established in 1990, is responsible for ensuring that water undertakers provide 'wholesome' drinking water. DWI assesses the sampling and analysis techniques and frequencies, and progress towards compliance with quality standards. DWI has a specific concern about what may be in the future raw water stream, together with associated water treatment needs and other compliance implications.

Local government perspectives

The primary perspectives of local government agencies relate to their legal responsibilities for planning, under the Town and Country Planning Act (1990) and the Planning and Compensation Act (1991). Local planning authorities must take full account of environmental issues when preparing policies and Structure Plans, including the protection of groundwater resources from the impacts of land-use policies and development plans. The local authority is obliged to consult with the NRA (in England and Wales) when preparing or amending a plan. Furthermore, local authorities are concerned to ensure that new development is assured adequate provision of water and wastewater services within the confines of sustainable environmental management. Local authorities have a particular responsibility for waste regulation, both issuing planning permission for landfill sites and regulating their use. As a consequence, they are very concerned about the issue of landfill. Box 5.1 lists the 13 most important issues, in order of priority, identified by the 18 local government respondents to the mail shot. The two highest priority issues relate to landfill and contaminated land. Local authorities also have statutory duties with regard to private groundwater supplies.

BOX 5.1 Local Government Perspectives

Landfill	●●
Contaminated land	●●
Subsurface methane	●●
Source protection	●
Remediation	●
Nitrate	●
Deep waste disposal	●
Vulnerability	●
Heavy metals	●
Acid mine drainage	●
Geochemical baseline	●
Wastewater reuse	●
Sewers etc	●

●● high priority ● priority

Regulator perspectives

The regulators are the guardians of the water environment. The River Purification Boards are the regulators in Scotland, the DoE (Northern Ireland) is the regulator in Northern Ireland and the NRA is the regulator in England and Wales. The NRA was established in 1989 and its innovative policy and strategy development is at the cutting edge of water-resources thinking in the UK. Nevertheless, this same development has brought into sharp relief the different perspectives within the institutional framework, and particularly the differences and gulf between the perspectives of the regulator and the supplier. Figure 5.2 illustrates this difference for groundwater, with the NRA focusing on the catchment area, infiltration, recharge, and unsaturated and saturated zone flow. On the other hand, the water supplier focuses on the source of supply, as the primary asset, and the delivery of services to the customer.

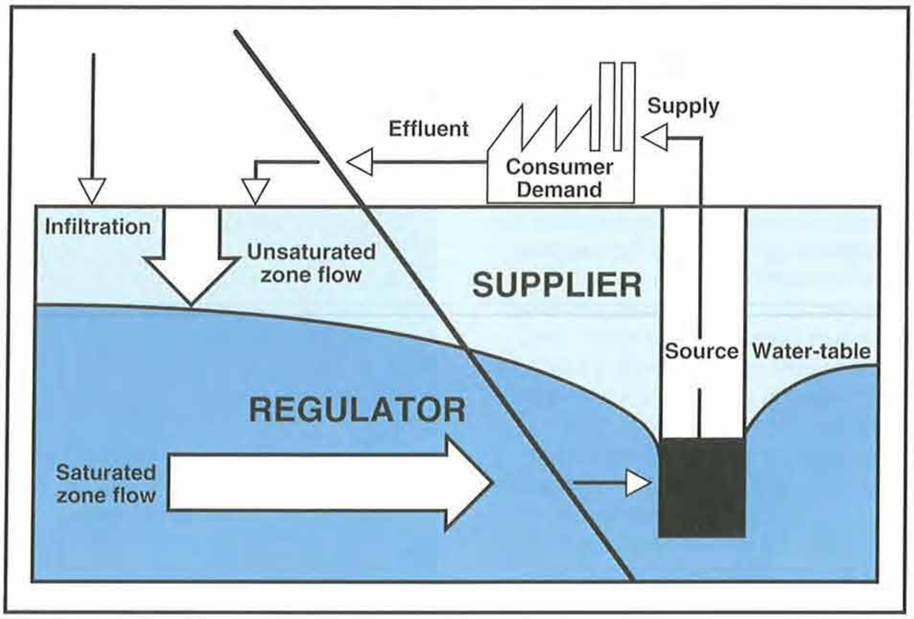


Figure 5.2 Different perspectives of the regulators and suppliers

Box 5.2 distils key statements of the NRA that relate to groundwater resources, drawing from statements of mission, aims and key policies and concepts. These excerpts provide an important backdrop to the NRA perspectives on groundwater issues.

In extensive face-to-face consultations with NRA regional staff, it was clear that their perspectives focused squarely on the complexities of fulfilling the mission of the NRA with regard to groundwater, a considerably more complex, less-well understood and less-readily assessed resource than surface water. Many of the emerging principles of water resources management (such as

BOX 5.2 NRA: Key Statements from Consultation Meetings

Mission

...protect and improve the water environment by the effective management of water resources and by substantial reductions in pollution...

Aims

...Achieve a continuing overall improvement in the quality of rivers, groundwater, estuaries, and coastal waters, through the control of pollution...

..Manage water resources to achieve the right balance between the needs of the environment and those of the abstractors..

Key policies and concepts

Sustainable development - no long-term systematic deterioration in the water environment due to water resource development and use.

Precautionary principle - where significant environmental damage may occur, but knowledge on the matter is incomplete, decisions made and measures implemented should err on the side of caution.

Demand management - the management of the total quantity of water taken from sources of supply using measures to control waste and consumption.

statutory water quality objectives, integrated pollution control, and 'polluter pays') are more difficult to apply to groundwater than surface waters, due to its three dimensional variability, uncertainty, lack of data availability and the timescales involved. Insufficient understanding and data - for example of groundwater flow regimes in drift-covered Chalk - can lead to unnecessarily precautionary decisions on source protection and abstraction licensing; this can then lead to conflicts with the water supplier and frustrations on the part of the regulator. The precautionary principle is routinely applied to groundwater resources, due to the large gaps in knowledge, and the lack of robust and standard guidelines for key determinations, such as for reliable yield. However, insufficient data or understanding of groundwater processes can lead to those precautionary decisions being unnecessarily conservative. The economic costs of these decisions can potentially be very significant. Targeting research to help minimise uncertainties should provide significant help in minimising the grey areas in such precautionary decisions, permitting development potential to be optimised without compromising sustainability.

BOX 5.3 NRA Perspectives

Low flows	●●
Vulnerability	●●
Source protection	●●
Wetlands	●●
Sustainable yield	●●
Pesticides	●●
NAPLS	●●
Contaminated land	●
Unregulated supply	●
Landfill	●
Microbiol. contamination	●
Nitrate	●
Afforestation	●
Acid mine drainage	●

●● high priority ● priority

BOX 5.4 Some NRA Perspectives on Key Groundwater Issues

- improved understanding of valley bottom hydrogeology required, so that baseflow/wetland - abstraction relationships can be defined and rational licensing controls adopted;
- the above supported by regional groundwater models, overcoming inconsistencies in local model boundaries and introducing vertical variations of hydraulic conductivity and specific storage and related parameters;
- recharge estimation, especially through drift;
- effectiveness of controls on nitrate pollution, and implications for amelioration;
- implications of pesticide contamination: compound mobility, flow paths, residence times, fate, new compound registration; etc;
- groundwater source protection zone definition and proactive inspection of areas of concern;
- consistent data availability.

Key issues and perspectives emerging from the consultations with NRA staff are given in Boxes 5.3. and 5.4. Many of these issues are shared with colleagues in the water industry, although the perspectives differ. In addition, NRA perspectives varied with the hydrogeological environments in different regions, for example:

- in Anglian, uncertainties presented by the drift are very important, affecting: Chalk-valley bottom and Chalk-wetland relationships; contaminant transport and groundwater source protection zone definition; and recharge and reliable yield determination;
- in Wales and the South West, the scale of private water supplies pose a particularly serious risk, and guidelines and/or procedures are sought for source protection, licensing and quality monitoring;
- in Severn-Trent, the Triassic sandstone aquifer is relatively slow to respond to pollutant loads (remediation is also relatively slow). Historic heavy abstraction and licences of right pose serious threats to environmental flows, which locally require compensation boreholes, and extensive agricultural and urban/industrial pollution legacies pose major threats to primary water supply sources. However, the Triassic sandstones do provide time to act, ie by pollution prevention and the changing of strategy before water supplies or the environment are detrimentally affected, provided that hazards are identified.

Overall, the NRA seeks to ensure that groundwater abstraction does not adversely affect the surface water environment. However, the state at which this environment is to be maintained is not generally defined and the impacts of controls on groundwater abstraction are rarely fully understood. In addition, the NRA seeks to protect groundwater from pollution by restricting activities which cause a threat in areas where groundwater is vulnerable and in the catchment areas of public supply sources. However, little is known about contaminant transport and fate in groundwater. In applying the precautionary principle, there is therefore considerable need for risk assessment. Ultimately, political and economic decisions are involved. What are the economic costs and benefits of protection? What level of costs over those of treatment can the national economy afford? What level of risk is acceptable in making judgements?

Six different Scottish River Purification Boards responded to the mail shot, and the 11 priority issues are listed in Box 5.5. Most of the expected priorities of a regulator are apparent (although pesticides were 9th); in addition, it is not surprising to see that afforestation and acid mine drainage are high priorities. Groundwater vulnerability mapping is planned in Scotland and a groundwater protection policy has been drafted. In Northern Ireland a groundwater protection policy is already in place. A groundwater vulnerability map was published in 1994 and a declaration regarding Nitrate Vulnerable Zones is due shortly.

Water service industry perspectives

In parallel with meetings with NRA staff, and sometimes together, extensive consultation meetings have also been held with specialist staff of the water industry. Although many issues similar to those of the NRA staff were raised, the perspectives were very different. One overall perspective that emerged was that, although the industry may wish to make decisions that are essentially environmentally sensible, in many cases the institutional and regulatory frameworks create serious disincentives to do this, due to the risks to business that may result.

First and foremost, the industry comprises businesses; supply boreholes are major physical assets and groundwater is a key tradeable commodity. Customers have growing demands for water and require minimised prices; they are also increasingly aware of water quality and environmental issues, and are willing to pay for improvements. While the borehole is a physical asset that requires appropriate management, access to raw groundwater is central to the business and licence 'claw back' in many parts of the country where resources are considered to be over-abstracted is a serious business threat. Licences of right are therefore guarded, as their loss may not be easily replaced, and may result in much higher costs for a distant or lower quality source. Major questions on groundwater resources posed by industry representatives are given in Box 5.6.

The quality of raw groundwater greatly affects the business, and uncertainty over contaminant transport in groundwater results in very difficult investment decisions for the industry. While the investment costs for nitrate treatment are reasonable (up to £3m for a 12 Ml/day plant), operating costs are very high, at eight times the normal treatment costs (£200 per Ml, against £25). In contrast, capital costs for pesticide treatment are three times higher (at about £4m), while operating costs are lower. In addition, costs are very sensitive to standards themselves;

BOX 5.5 River Purification Board Perspectives

Acid mine drainage	●●
Contaminated land*	●●
Nitrate*	●●
Afforestation	●●
Low flows	●●
Source protection	●●
Landfill*	●
Sewers etc*	●
Pesticides	●
Vulnerability	●
Land use change	●

●● high priority ● priority

*These items, with the addition of Remediation, were presented as the perspectives of the regulator in Northern Ireland (the Environment Service, DoE/NI)

BOX 5.6 Key Industry Questions on Groundwater Resources

- what is an accurate basis for assessing recharge and determining the reliable yield of a catchment?
- what is the actual impact of abstraction reduction on streamflow and wetlands in any given case?
- what is the environmental and economic rationale for adoption of a specific minimum acceptable flow?
- can higher abstraction be allowed through carefully engineered return flows?
- what role can groundwater storage augmentation through artificial recharge play in increasing catchment yields?
- is the water industry to bear the cost of 'improving' naturally ephemeral streams and occasional (and natural) drought impacts?

BOX 5.7 Key Industry Questions on Groundwater Quality

- are the standards for common contaminants justified on epidemiological and economic grounds and can minor changes be made with minimal impact?
- what nitrate concentrations are to be planned (and invested) for at individual sites and within blending groups?
- will nitrate controls work in bringing down concentrations - by how much and when?
- why are nitrate concentrations so variable, both laterally and vertically?
- what is the residence time in groundwater of different pesticides?
- can we wait a few years only for pesticide concentrations to fall or must investments in treatment be made?
- what is the extent of and where is the pesticide legacy and when will it appear?
- similar questions for industrial contaminants: where, when; how much and for how long?
- in general, can pollution risk inventories and proactive action in source catchments improve investment decisions and consequences?

small changes in standards for a particular contaminant can have major cost implications for the industry. Box 5.7 lists key questions posed regarding groundwater quality.

The major problem is nitrate. The damage has already been done, so that mitigating measures and time are needed to undo the damage. When can maximum nitrate levels be expected at source? In the meantime, blending is widely practised and some sources are mothballed, to be used - at high operating cost - when needed, such as in drought.

Pesticide problems are rapidly assuming the same scale as nitrate, although the source is generally thought to be primarily (but not exclusively) non-agricultural. Very high capital costs are being made in treatment, although the timescale of treatment needs is unknown. Although the atrazine problem appears to be fading (due to its banning), its substitute diuron is just appearing, and the fate of these and other pesticide compounds in groundwater is unknown. Planning investments in pesticide treatment is thus very risky.

Industrial contaminants represent another problem, in that timescales are likely to be very long and there is very little known about what is on the way - or will be on the way, when it will arrive and how long it will keep coming. It is generally considered that all pre-1985 high-risk industries will have contaminants in the ground. In addition, it is considered that there are major - punitive - disincentives today for polluters to report a spill, greatly increasing the risks to supply sources.

Clearly, uncertainties over the groundwater environment lead to decisions on treatment that have major cost implications. Treatment research offers considerable potential for cost saving, as would 'cut-out' alarms for unexpected contaminant arrival at source. Ultimately, however, knowledge of the groundwater system and guidelines for managing different contaminants in groundwater would provide the most rational way forward for the water industry. In consultation meetings, it was clear that industry representatives were primarily concerned with what would happen at their sources and when, but that there was only limited acceptance of the need for understanding the groundwater system up-gradient of the supply boreholes. Obviously, an answer to the former requires a knowledge of the latter.

BOX 5.8 Water Industry Perspectives

Pesticides*	●●
Nitrate*	●●
Low flows*	●●
Borehole efficiency	●●
Source protection*	●●
Sustainable yield*	●●
Contaminated land	●
Landfill	●

●● high priority ● priority

* The water undertaking in Northern Ireland (DoE/NI's Water Executive) identified these items as priority, with the addition of vulnerability.

Box 5.8 summarises the mailshot responses of the water industry (16 in total), listing the eight most important issues (other issues received very low 'scores'). All the high priority items clearly relate to the primary asset, the source, ensuring its protection from contamination, particularly from nitrate and pesticides, providing the basis for its licensed abstraction, and ensuring its efficient performance.

In conclusion, a further overall perspective gained from discussion with the water industry is concern that the public image of groundwater is low, and its benefits (relatively high reliability, security and quality and low cost) not fully appreciated. It was thought that excessive groundwater abstraction is generally regarded as the culprit for deterioration in the aquatic environment, irrespective of the role of land-use change, valley drainage and river engineering, and the recent severe drought. While this image is considered to have been fostered by the 'green lobby', it is thought to have been accepted by the NRA, prejudicing decisions on groundwater management. In the view of many in the industry, there is a need to build public confidence in groundwater and increase awareness of its nature and role. Linked economic and hydrogeological analysis would illustrate the costs and benefits of groundwater development against alternative options.

Other perspectives

This section seeks to distil the perspectives of other key, but nevertheless smaller, players within the institutional framework, who have less broad responsibilities and therefore somewhat narrower perspectives. It is clear that reconciling different perspectives is not generally possible, as the trade-offs between environmental protection, economic development and social benefit are perceived differently by different stakeholders. Nevertheless, clear policies and transparent decisions based on sound analysis will reduce conflict.

Environmental non-governmental organisations (NGOs) are extremely concerned about the degradation of rivers and wetlands and the implications for wildlife and their habitats. A particularly important characteristic is the position of the water table relative to the land surface, as lowering water tables can greatly affect fauna (such as wading birds), flora (such as submerged *Ranunculus sp.*) and soils (such as peat). In general, the perception is that reduction of groundwater abstraction (including through legislative change to permit

BOX 5.9 Environmental NGO Perspectives

Wetland conservation	●●
Acidification	●
Low flows	●
Land-use change	●
Landfill	●
Source protection	●
Nitrate	●
Afforestation	●

●● high priority ● priority

revocation of licences of right), relocation of boreholes, artificial recharge and improved surface storage are all instruments that must be employed to mitigate the environmental damage caused by excessive groundwater abstraction in sensitive areas. Key research needs are perceived as quantifying the impacts of abstraction, lowered water tables, and reduced baseflow on ecology, including the development of predictive models and of site-monitoring protocols. Box 5.9 lists eight key issues identified by the seven environmental NGOs who responded to the mail shot; the issue of wetlands was clearly the highest priority. In addition to these NGOs, there are other interest groups who generally share these perspectives; these include the many 'low-flow societies' that have emerged in recent years, which include property owners and fishermen etc.

Industry groups, for example those representing landowners and farmers, and fertiliser manufacturers and other branches of the chemical industry, are concerned about the restrictions placed on agricultural and industrial activity and associated 'land blight' as a result of nitrate controls and other groundwater protection practices, which restrict land development. For example, with regard to nitrate, the case is made strongly that: the MAC value of 50 mg/l should be replaced by an average value; a balance should be sought between agricultural measures and treatment/blending; and nitrate vulnerable zones must be precisely defined, carefully monitored and revoked if appropriate, and farmers fully compensated. Industries are generally keen to take a sustainable perspective, where possible, although again the economic and commercial consequences of adopting an open and rational approach to, say, clean up of contaminated land and groundwater can be very threatening.

The research community is very concerned about the state of groundwater research in the country. First, it is considered that there is no clear responsibility for funding and commissioning the underpinning strategic science that is a prerequisite for resolving the applied issues addressed in this report, and that there is little recognition of the importance of this work. Second, there is concern about the short term and fragmented nature of research under way, with little longitudinal field-based study and new data gathering, and limited information sharing between research commissioning organisations. This tends to lead to little advancement in knowledge and possible duplication of effort. Third, there is a concern that commercial, competitive tendering of R&D is more appropriate for the D than the R, and it is believed that successful, long-term programmes of R&D will prove difficult to manage in this way. UK groundwater research has a long history and a good record, and the research community is concerned to maintain this, thereby contributing to the future management of an economically and strategically important natural resource.

Consultants provided very valuable contributions to this Study, although there is no obviously discernible trend in perspectives among the consulting industry on groundwater issues and research needs. These perspectives will clearly be a function of the area of business activity of a particular firm or individual.

Public perspectives on groundwater appear few, and, as discussed above, tend towards a concern that groundwater abstraction is a culprit for many of the problems of the water environment. Few people know or care where the water in their taps comes from, and, while surface water is valued for amenity and aesthetic reasons, groundwater is 'out of sight and out of mind'. There is also little perception of the timescales involved in groundwater processes. This is despite the fact that an appreciation of groundwater has been an integral part of our culture and folklore for centuries; ready access to wells and springs has been the single most important factor in human settlement for millennia and numerous place names, 'holy wells' and old village pumps are evidence of that. One exception to the apparent disinterest is indicated by the very rapidly increasing demand for bottled 'natural mineral water', defined by EC Directive 80/777 as *'a microbiologically wholesome water originating in an underground water table or deposit and emerging from a spring tapped at one or more natural or borehole exits... '*. Thus all natural mineral waters are groundwaters - although not all groundwaters are natural mineral waters.

For mineral water bottlers microbiological contamination is an important issue, as they are unable to chlorinate their supplies. The same is true for most private water supply users.

6. Identifying priority issues

This Chapter seeks to set some priorities among the wide range of issues and perspectives discussed above, in order to allow the development of a rational research agenda that meets the major needs of the nation and of the different responsible parties. In setting priorities, it is important not to rule out other items, which may well have a place in a well-structured research programme of an individual institution or group of organisations.

The goal here, however, is to identify those issues where maximum benefit to the nation would be gained from investments in researching their solution. This does not, of course, preclude the need for good research design and management in order to ensure cost-effectiveness and value for money. It is clear that this exercise remains subjective, although considerable effort has been made to increase objectivity through consultation and transparency.

It is relevant to add here that many consultees regarded there to be a difference between 'perspectives' and 'reality'. For example, the 'landfill issue' was rated very differently by different institutions - does this imply the need for the better communication of existing knowledge rather than for new research? In another case, it was argued that the regulators should set the research agenda as they have the necessary information to do so; other institutions only have 'relatively uninformed opinion'. However, the extensive correspondence received in finalising this Report showed substantial variation in opinion, even from within one 'element' of the institutional framework; there are thus very different views on the nature of 'reality'. The Report therefore takes a different tack. Given the importance of groundwater resources and the very significant gaps in knowledge, 'perspectives' become a good surrogate for 'reality'; ie problems that are perceived to be serious are problems that need to be investigated in one way or another. In adopting this approach, however, it is important to note where research has already been extensive, as in the case of the nitrate issue, and to note the need for good dissemination of the findings of completed research.

In Chapter 3 thirty-one issues affecting groundwater resources are examined briefly; they are covered in greater detail in a separate volume, the *UK Groundwater Issues Report*. For each of these issues, it is possible to identify whether the problem is one of generally increasing, stable or decreasing scale. Clearly, issues of increasing scale are a cause of greater uncertainty (though not necessarily of greater concern) than those that are of stable or decreasing scale.

Similarly, for each issue it is possible to identify where we are on the learning curve, ie whether there is a limited understanding of the issue, some understanding or well-developed understanding. In Chapters 4 and 5, the national, regional and institutional perspectives on the issues are discussed. From this discussion, it is also possible to sort the issues generally into three categories of importance - ie of least, average or most importance. Box 6.1 gives the results of this exercise, ranking all the issues by status (importance), trend and learning curve.

The priority issues, underlined and highlighted by bold text, have been selected as follows:

a. all of the issues that are ranked of major importance, irrespective of trend and learning curve;

b. all of the issues ranked as average importance and having a trend of increasing scale.

Fourteen issues are thus identified as priorities for research. These are further discussed in the next part of the report, *Science and Research*.

BOX 6.1 Summary Table Illustrating the Importance and Level of Understanding of the Groundwater Issues

Issues	*Status*	*Trend*	*Learning Curve*	*Issues*	*Status*	*Trend*	*Learning Curve*
<u>Acid Mine Drainage</u>	2	^	2	Rad. Waste Disposal	2	–	1
Acidification	1	–	2	Radon, Radium ... etc	1	–	2
<u>Afforestation</u>	2	^	2	Sewers etc	3	–	3
Climate Change	1	^	3	**<u>Sustainable Yield</u>**	3	–	2
<u>Contaminated Land</u>	3	^	2	**<u>Remediation</u>**	2	^	3
Deep Waste Disposal	2	v	2	Rising Water Levels	1	–	1
Heavy Metals	2	–	2	Saline Intrusion	1	–	1
Quarrying	2	–	1	Sludge Utilisation	2	–	2
<u>Landfill</u>	3	v	1	**<u>Source Protection</u>**	3	–	2
<u>Land-Use Change</u>	2	^	2	Subsurface Methane	1	–	2
<u>Low Flows</u>	3	–	2	Unregulated Supply	2	–	2
Microbiol. Contamn.	2	–	3	**<u>Vulnerability</u>**	3	–	2
<u>NAPLs</u>	3	–	2	Wastewater Reuse	1	^	3
Geochem. Baseline	2	–	2	Borehole Efficiency	2	–	2
<u>Nitrate</u>	3	v	1	**<u>Wetland Conservation</u>**	3	^	2
<u>Pesticides</u>	3	–	2				

Key:

Status: 1 = least important issues ; 2 = issues of average importance; 3 = issues of major importance

Trend: ^ = issues of increasing scale; – = scale neither increasing or decreasing; v = issues of decreasing scale

Learning Curve: 1 = well-developed understanding; 2 = some understanding; 3 = limited understanding

7. Linking issues and science

Introduction

The Report has so far concentrated on the first objective of the Study: the identification of *issues*. This Chapter seeks to link issues to the underpinning science. Understanding the issues - their extent, impact and/or resolution - relies heavily on the application of scientific principles. For example, understanding many of the groundwater issues involves a detailed knowledge of groundwater flow and the types of chemical reactions that occur in aquifers. This understanding of scientific principles and processes is particularly necessary for groundwater as its remoteness and the cost of access (eg for measuring or sampling) means that deductive and predictive analysis (ie inference) is much more important than for surface water, where extensive measurement can be readily made.

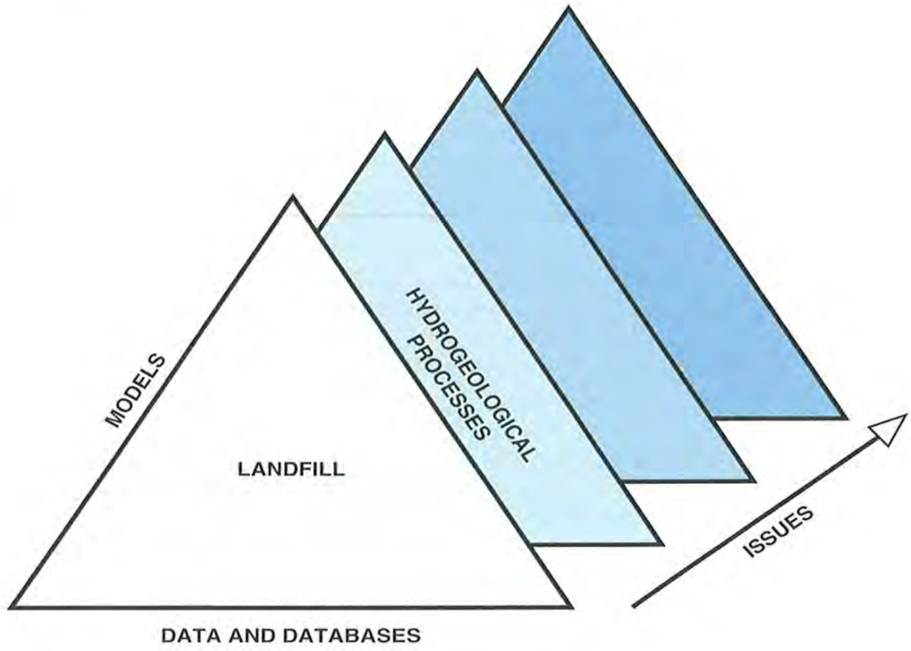


Figure 7.1 A framework for linking groundwater issues to the underpinning science

Fundamental advances in basic science such as in statistics, numerical analysis, geology, analytical chemistry and instrumentation, geophysics and microbiology can all have important repercussions in groundwater science. These advances may, for example, be in terms of new theoretical approaches or of advances in monitoring. However, knowledge of the underlying processes alone is not sufficient to provide practical solutions to problems. These processes must be combined with some kind of model which links the processes together in a meaningful way and with data and databases which define certain key properties or parameters of the particular issue being considered. Finally, there must be an overall approach or methodology (eg risk analysis) which defines the way in which these three components are brought together to solve a particular problem.

These elements come together in Figure 7.1. This figure shows schematically how the scientific approach to each groundwater issue combines information on the hydrogeological processes involved, the relevant data and databases and the range of models that is available. Each issue is addressed by a unique combination of these three elements, brought together using an appropriate methodology for the issue in hand. Each of the elements is thus an inextricable part of the scientific foundation needed to understand and resolve each groundwater issue and is described briefly below.

Hydrogeological and basic processes

The most complex of the elements are the Hydrogeological Processes, which include a broad range of applied scientific topics. The key Hydrogeological Processes are described in Box 7.1. It is important to emphasise that the processes all interrelate, and to some extent overlap; however, each is sufficiently important in its own right to deserve separate attention.

Each of the issues requires a greater understanding of some of these processes than others: the importance of the various Hydrogeological Processes to addressing each of the issues is indicated in Box 7.2. This Box must not be seen to be comprehensive. It does, however, demonstrate the key point that research work on, say, reactive transport is not only strategic science but is also an essential component of applied scientific research on topics such as acid mine drainage, landfill and pesticides.

The various Hydrogeological Processes, which are identified above, can themselves be subdivided further into a number of different basic scientific processes. These basic processes, along with their associated data requirements, are listed in Box 7.3. For example, understanding saturated flow needs data on the spatial distribution of permeability and porosity. Reactive transport requires knowledge of the major geochemical processes such as acid-base reactions, redox reactions and sorption as well as of a great deal of fundamental chemical thermo-dynamic data. Much of the research into these basic processes and the associated data collation is carried out by non-groundwater scientists.

This results in a hierarchical approach to the science underpinning the resolution of groundwater issues, leading from the fundamentals of physics, chemistry and biology through to the Hydrogeological Processes. There is a two way flow of information between these areas of science: the basic sciences feed the

BOX 7.1 Hydrogeological Processes

Soil processes

Groundwater recharge enters the unsaturated zone through the soil. The soil and vegetation are important in determining the amount and timing of groundwater recharge and its quality. The soil forms an important barrier against groundwater pollution but contaminated soils can also be a potential long-term source of polluted groundwater. The soil contains a large number of microorganisms which carry out important transformations, eg organic nitrogen to nitrate, degradation of toxic organic substances, consumption of oxygen and production of carbon dioxide.

Unsaturated zone flow and transport

The unsaturated zone of UK aquifers is often 10-50 m deep. Since the rate of flow of water through the unsaturated zone of many UK aquifers is in the order of 0.5 to 1.5 m per year, the unsaturated zone provides an important delay between input of a contaminant at the soil surface and when it finally reaches the water table. Although the unsaturated zone contains less organic matter and fewer microorganisms than the soil, its adsorbent properties and capacity for degradation may provide an additional barrier against many contaminants. Aquitards can significantly affect recharge and contaminant migration to the water table.

Saturated zone flow and transport

Understanding the rate and direction of groundwater flow in an aquifer is a key part of most hydrogeological investigations. Frequently this information is derived from a computer model. Such models require a detailed understanding of the physical properties of the aquifer, preferably in 3-D. Although the saturated zone of aquifers can be more than 100 m deep, the hydraulically active part is often concentrated in the top 50 m. Modelling flow within an aquifer often has to be based on sparse field observations and inadequate characterisation of the aquifer heterogeneity. Flow predictions based on such models therefore have a considerable degree of uncertainty. Predicting the movement of chemicals in aquifers is even more demanding. Aquitards have a strong influence on flow directions and contaminant pathways.

Reactive transport

Many, but not all, chemicals are sorbed on the aquifer matrix or undergo chemical reaction during transport so delaying their arrival at a groundwater pumping station. In the case of some organics, such as pesticides, this delay may be such that all of the chemical has had time to degrade by the time it reaches the pumping station. Quantifying the extent and rate of such reactions is critical in understanding the long-term fate of many groundwater pollutants. It is one of the most active areas of current groundwater research.

Microbiology

Subsurface microbiology is a relatively new science but there is now ample evidence to show that a wide range of microorganisms are present and probably active in UK aquifers. However, it is difficult to quantify exactly how active they presently are. Microorganisms are responsible for a number of important transformations, including most redox reactions, such as organic carbon oxidation, denitrification, methane production etc. The *in situ* microorganisms can sometimes be stimulated to increase the rate of breakdown of a biodegradable groundwater contaminant. Such bioremediation can be quite efficient in shallow aquifers.

Fracture flow

The major UK aquifers are all fractured to some extent, with fracture flow dominant in some. Such fractures can lead to preferential flow of water and dissolved chemicals, and can lead to fast pollutant transport. The yield of pumping boreholes is often mostly derived from the rapid flow of water through fractures. The importance and extent of fracture flow is often difficult to model as it is very sensitive to the assumed fracture sizes, spacing and distribution.

Multiphase flow

Petrol and many organic solvents do not mix with water and so flow through aquifers as a separate phase. Since petrol is lighter than water, it will tend to accumulate close to the water table. Many solvents are denser than water and so will tend to sink to the bottom of an aquifer, often very rapidly. Most of these organic substances are slightly soluble in water and so also get transported with the groundwater flow. They are also volatile and will partition into the gas phase. Knowledge of the flow of such chemicals is important for understanding their fate in aquifers and in designing clean-up programmes. Modelling such flow is difficult.

Gas exchange

Below the soil there is relatively little exchange of gases with the atmosphere. Some major gases, such as oxygen and carbon dioxide, are important in determining the geochemical environment of an aquifer. Some trace gases, such as radon and methane, can be potentially dangerous. Others such as the various nitrogen gases can provide clues to the biological transformations of nitrogen species taking place. At contaminated sites, the transport of organic vapours may be important in pollutant migration and remediation. Gases move by diffusion and convection both in the gas phase and in the dissolved phase.

BOX 7.2 Relationship Between Groundwater Issues and Dominant Hydrogeological Processes

ISSUE	HYDROGEOLOGICAL PROCESS							
	Soil processes	Unsatd flow & transport	Satd flow & transport	Reactive transport	Microbiol	Fracture flow	Multi-phase flow	Gas exchge
Acid mine drainage				●	•	●		●
Acidification	●	•		●				
Afforestation	•	•		•				
Climate change	•	•	●					
Contaminated land	●	•	•	●	•	●	●	•
Deep disposal			•	•		●	•	•
Heavy metals	●	•	•	●		•		
Quarrying		•	●			●		
Landfill		•	●	●	●	●		●
Land-use change	●	•		•				
Low flows	•	●	●					
Microb. contamn		●	•		●	•		
NAPLs		•	●		•	●	●	●
Geochem. baseline	•		•	●		●		
Nitrate	●	●	●	•	●	•		•
Pesticides	●	●	●	●	●	●		
Rad. waste disposal			•	●		●		
Radon, radium...		•	●	•		•		
Sustainable yield		●	•			●		
Remediation	•	•	•	●	●	●	•	●
Rising water levels		•	●			•		
Saline intrusion			●	•		•		
Sewers...	●	●			●			
Sludge utilisation	●	•	•	•	•	•		
Source protection	•	●	●	●		●	•	
Subsurface methane			•		•	●	●	●
Unregulated supply	•	•	•		•	●		
Vulnerability	●	•	•	●	•	●	•	
Wastewater reuse	●	●	•	●	●	•		
Borehole efficiency			●			•		
Wetlands	●	•	●			•		

● major processes • less important processes

BOX 7.3 Characterisation of Hydrogeological Processes

HYDROGEOLOGICAL PROCESS	BASIC PROCESSES, PARAMETERS, MODELS & ASSOCIATED DATA REQUIREMENTS
Soil processes	**Evaporation and recharge, nutrient uptake, mineralisation of organic matter, humics, ion exchange and sorption, heterogeneity, acid-base equilibria, CO_2 production, mineral weathering, formation of secondary minerals, contaminated soil characterisation, bioavailability and toxicity, clean-up, hyperaccumulator plants**
Unsaturated flow	**Preferential flow, non-Darcian flow, transfer functions, stochastic hydrology, geostatistics & transport, groundwater-surface water interactions, unsaturated hydraulic conductivity, diffusivity, hysteresis, aquitard behaviour**
Saturated flow & transport	**Permeability, porosity, dynamic porosity, dynamic storage, spatial variability, geological control, flowpaths and mixing, density-driven mixing, geochemistry, connate waters, groundwater 'age', isotopes, diffusion and dispersion, equivalent porous medium flow models, double porosity & double permeability models, formation factors, aquitard behaviour**
Reactive transport	**Acid-base & redox reactions, mineral solubility and precipitation, solid solutions, surface chemistry, facilitated transport, rate-limited sorption, rate-limited dissolution, thermodynamic databases, partition coefficients, surface binding constants and site densities, structure-activity relationships, heterogeneity and non-linear sorption, humics, isotopes, diffusion coefficients and tortuosity, dispersion coefficients, hydrolysis**
Microbiology	**Biodegradation and transformation, redox reactions, diffusion, reaction pathways, microbial biomass, microbial adsorption, preferential flow, rate constants, temperature dependence, microcosm studies, remediation**
Fracture flow	**Fracture size, spacing, aperture and orientation distributions, fracture surface characteristics, flow pathways, tracer tests, breakthrough curves, fracture chemistry, fracture models, network models, channel models**
Multiphase flow	**Wettability, dissolution, volatilisation, residual saturation, solubility, densities, geophysics, relative permeability**
Gas exchange	**Gas and vapour diffusion, convection (gas venting), Henry's Law partition coefficients, gas density gradients, non-ideal transport and rate-limited sorption**

applied sciences with new ideas while the applied sciences such as hydrogeology stimulate new solutions to practical problems from the basic sciences.

Models

Modelling is not an end in itself, it is part of a wider process of decision making. There are a variety of types of model designed for different end purposes. These range from management models, which aim to provide guidance to management about the consequences of various courses of action, to research models, in which the main purpose is to aid our conceptualisation and understanding of the processes taking place so that extrapolations can be made to new and unknown situations. An increasingly important use of models is in risk assessment which attempts to use scientific understanding of an issue and the consequences of various courses of action in terms of the risks posed. Models are not a substitute for data collection or human decision-making. Models can range from simple operational 'rules of thumb' to sophisticated research models aimed at increasing the understanding of the underlying processes. Each of these models has its own requirements in terms of data and degree of specialist input and each is appropriate for different end users.

Data and databases

All hydrogeological models have certain data requirements. These could include physical parameters such as the density of water, the porosity and transmissivity of an aquifer and chemical parameters such as thermodynamic data, partition coefficients and biodegradation rates. Such data are often crucial to the success of a model and may be difficult to obtain independently. Other data are not aquifer-specific and can be obtained from generic databases. Spatially variable parameters must be obtained from the appropriate databases. These may need to contain data covering all three dimensions.

Many of the data contained in the generic databases are based on laboratory determinations of key parameters. In other cases, these parameters must be derived from field observations. An important issue in hydrogeology is how to generalise from field observations made at a few sites to the aquifer as a whole, given the high costs of data collection as well as the generally heterogeneous nature of most aquifers. It is often necessary to estimate the values of some parameters indirectly from other related parameters. Establishing useful relationships for interpolation and extrapolation is becoming more important as models and modelling approaches (eg GIS) become more demanding.

8. Defining the R&D agenda

Introduction

This Chapter addresses the second objective of the Study: defining the groundwater research, development and monitoring needs. These are referred to collectively as the R&D agenda. The objective is to define the agenda for all groundwater research customers and researchers:

- to address the issues; and
- to ensure underpinning knowledge of UK aquifers.

This task is a complex one as there are many potential research customers (funders) in the public and private sectors, with new potential markets emerging (such as the insurance industry). Each customer may have an entirely different perspective, as discussed in Chapter 5, and therefore *apparently* different research needs. This is, however, not the case, as the problem to be investigated is generally the same, although the perspective may be different (as may be the hoped-for results); farmers, regulators and utilities all have an interest in nitrate transport and denitrification, for example. There are also many different research organisations, who tend to view research from the 'bottom up', and not in terms of issues. There are dangers inherent in defining research needs only in relation to potential customers, as there are in defining research in relation to potential researchers (ie contractors). There is also a case to be made that groundwater is a complex natural resource whose more effective management would bring significant benefit to society and the environment and there is therefore a rationale for a unified research agenda. Box 8.1 summarises some of the reasons for the unified agenda which the remainder of this Chapter seeks to develop. In contrast, there may be good reasons for not seeking a unified R&D agenda, such as conflict of interest between funding organisations.

There are many different ways in which this discussion of research and the categories of research themselves could be presented. Whichever way is adopted, the result cannot be simple, as there are so many cross-cutting layers of activity. This Chapter seeks to keep the structure as simple as possible, without losing essential detail. It starts by considering the research needs of the *priority groundwater issues*. For each priority issue, the R&D needs are broken down into *Operational Research* and *Applied Research*. Underpinning *Hydrogeological Process Research* is also considered. *Basic Process Research* - described in Box 7.3 above and primarily rooted in the basic physical, chemical and biological sciences - is too generic and diverse to be considered in this Study. Other divisions of work are possible. For example, all monitoring or modelling needs could be considered together. However, within the scope of this Study, these divisions are also too broad for detailed consideration and prioritisation. These are therefore considered as types of R&D activity within each Hydrogeological Process. They are referred to as *Research Tools* and are discussed briefly in Chapter 9.

BOX 8.1 Rationale for a Unified R&D Agenda

- Groundwater is still only partially understood and groundwater research is expensive and slow, with data relatively difficult to obtain.
- For the same issue, common R&D will be needed, irrespective of the customer and perspective.
- For different issues, similar R&D is often involved, particularly where underpinning hydrogeological processes are the same.
- Multiple funding of a broad R&D agenda is likely to be cost-effective, particularly given scarce resources.
- Shared funding of individual R&D topics will avoid duplication and accelerate learning, both reducing costs.
- The monitoring infrastructure and databases needed are common to related topics.
- There is a need to identify and prioritise underpinning basic R&D.
- Some R&D funding is provided across broad programmes of work consisting of interrelated sub-projects (eg via NERC *Special Topics* and *Community Programmes*).
- Research institutions are structured into groups which specialise in certain areas; contractor consortia will foster and not dissipate these skills.

In summary we consider:

- *Operational Research:* research directly aimed at delivering tools for groundwater management and development, generally viewed as a priority by the managers and users of the resource.
- *Applied Research:* discrete research into key areas of the particular issue, often but not invariably a prerequisite for the operational research to be effective.
- *Hydrogeological Process Research:* underpinning research into generic processes in the groundwater system which may relate to many different issues and which will provide essential underpinning knowledge of UK aquifers. *Basic process research* may form an integral part.
- *Research Tools*: methods, technologies and activities requiring special skills and/or infrastructure

(inc. equipment) which are common to Applied Research and to Hydrogeological Process Research; research may, of course, also be necessary to develop and refine some research tools. These research tools are further discussed in Chapter 9.

These categories and their interrelationships are shown in Figure 8.1.

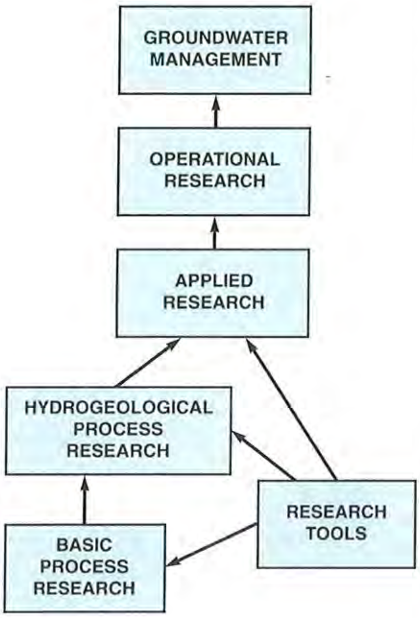


Figure 8.1 The research categories in the Report

Addressing priority issues

The principal research requirements that are needed to advance our understanding of the 14 priority issues were identified during the writing and review of the various 'Issues Papers'. These research requirements were further refined during a Science Seminar attended by leading groundwater scientists from four universities (Imperial and University Colleges, London; Birmingham; East Anglia; and Reading), three research institutes (WRc; IH; and BGS) and two research customers (NRA and FWR). The Seminar was held in Wallingford in January 1995 as part of this Study.

The conclusions from these discussions are summarised in a series of tables, (Tables 8.1 to 8.14) one for each priority issue. These list the *Research Objectives*, the *Operational Research Requirements*, the *Applied Research & Data Requirements* and the underlying *Hydrogeological Processes* involved. They also show in very broad terms the main beneficiaries of the research, its approximate costs and timescales involved.

The *Research Objectives* indicate the overall objectives of a unified research programme to resolve the issue. The *Operational Research Requirements* indicate the operational products of research required for issue resolution, generally representing the needs and perception of the principal research customers and beneficiaries. The *Applied Research & Data Requirements* indicate the more detailed topics needing research in order to fulfil the *Research Objectives,* generally representing the perception of the research scientist.

The estimated costs are based on a broad assessment of the minimum *annual* cost of an effective research programme. These costs have been classified as Low (less than £100k per year), Medium (£100k to £1m per year) and High (more than £1m per year). In general, projects requiring field observations are relatively expensive because they tend to be labour-intensive and require expensive services or equipment, eg the drilling of boreholes or continuous monitoring. It is emphasised that these cost estimates are very approximate and are given to provide relative scale only.

The timescale indicated gives the estimated amount of time required before significant progress can reasonably be expected. Again the estimates are very approximate and will vary depending on sites, pre-existing data etc. This scale has been divided into three categories: Short (1 year or less), Medium (1 to 3 years) and Long (more than 3 years). Investigations where the procedures are straightforward may be able to be completed in a year or less, whereas research programmes where new procedures need to be developed and tested, normally require at least a three-year programme. The timescale required for modelling and laboratory-based studies depends very much on whether new software or new experimental methods need to be developed. Programmes involving major new initiatives, such as field monitoring, usually require a longer timescale in order to repay the initial effort involved in setting them up and to gather sufficient data to be of relevance for longer-term predictions, eg to obtain a representative range of climatic conditions.

The research needs for the various priority issues are given in Tables 8.1 to 8.14 over the next seven pages.

TABLE 8.1

ACID MINE DRAINAGE

Beneficiaries: C,R,I,E

RESEARCH OBJECTIVES

To improve our understanding of the impacts of mine/minefield closure on groundwater and the processes controlling the scale and extent of acid mine drainage (AMD) in order to identify risk and design mitigating actions.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• predictive tools for assessing the impact of mine/minefield closure and the subsequent pumping regime on groundwater quality in adjacent aquifers and on the seepage of acidic mine waters to surface water courses, including scale and longevity, and then formulation of abandoned mine/minefield protocols and groundwater management strategies for the mitigation of AMD on groundwater	£££	L

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• broad survey of the scope and scale of the AMD problem and identifying areas where adjacent aquifers will be affected and possible acidification 'hotspots'	££	M
• improve understanding of the mechanics of flow in abandoned mines by monitoring and modelling	££	M
• investigation of geochemical processes occurring during generation and subsurface transport of AMD	££	M
• development of coupled models of flow and chemistry in abandoned deep-mined strata	£	S
• rigorous analysis of geotechnical problems arising from groundwater rebound in abandoned mines	£	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Reactive Transport	Microbiological Processes
Fracture Flow	
Gas Exchange	

Key: *Beneficiaries/funders*
C - Water Utilities; E - Environmental NGOs; G - Government; I - Industry & Users; R -Regulators; N - Research Councils
Annual cost: £ - Low; ££ -Moderate; £££ - High
Time: S - Short; M - Medium; L - Long

TABLE 8.2

AFFORESTATION

Beneficiaries: R,E,C,N,I

RESEARCH OBJECTIVES

To understand recharge and chemical processes that are affected by afforestation and thus identify the impact on groundwater quality and quantity.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• develop predictive tools to assess the impact of afforestation on groundwater quality and quantity and determine appropriate forest and groundwater management strategies	£	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• improved process models for forest evaporation based on theoretical studies with calibration against field studies	££	M
• establish extent of recharge under various climates, broadleaf species and soil types for both major and minor aquifers	£	S
• investigate influence of forest size and the mosaic structure of many new forests on recharge and water quality including any 'edge' effects	££	M
• quantify nitrate leaching under a variety of broadleaf species at various stages of the forest management cycle	£	M
• quantify the extent and consequences of continued soil acidification on groundwater	£	M
• evaluate impact of various forest management strategies (pesticides, fertilisation and sewage sludge applications) on groundwater quality	£	L

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
	Soil Processes
	Unsaturated Flow & Transport
	Reactive Transport

Key: *Beneficiaries/funders*
C - Water Utilities; E - Environmental NGOs; G - Government; I - Industry & Users; R -Regulators; N - Research Councils
Annual cost: £ - Low; ££ -Moderate; £££ - High
Time: S - Short; M - Medium; L - Long

TABLE 8.3

CONTAMINATED LAND

Beneficiaries: C,R,I,E

RESEARCH OBJECTIVES

To improve our understanding of the processes of groundwater pollution from contaminated land, and the extent of the problem, in order to classify risk and to identify mitigation strategies.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of tools to assess risk to groundwater sources and management strategies to identify and implement economic and effective mitigation actions	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• survey the extent of groundwater pollution from contaminated land	££	M
• monitoring the effectiveness of clean-up procedures	££	M
• factors controlling the migration of contaminants through soil cover	£	S
• study of unsaturated and saturated zone pollutant transport processes	££	L
• biogeochemical processes and *in situ* rates of degradation	£	S
• threat of remobilisation of historic contamination	£	M
• development and testing of reactive transport models	£	S
• study of recharge and runoff and their influence on the threat to groundwater	£	S
• development of standard leachate tests & soil gas survey methodology for characterising soil and aquifer contamination	££	S
• establishment of a site(s) to implement applied research programme	£££	L

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Soil Processes	Unsaturated Flow and Transport
Reactive Transport	Saturated Flow and Transport
Fracture Flow	Microbiological Processes
Multiphase Flow	Gas Exchange

Key:

Beneficiaries/funders		*Annual cost*	*Time*
C - Water Utilities	I - Industry & Users	£ - Low	S - Short
E - Environmental NGOs	R -Regulators	££ -Moderate	M - Medium
G - Government	N - Research Councils	£££ - High	L - Long

TABLE 8.4

LANDFILL

Beneficiaries: G,I,R,E

RESEARCH OBJECTIVES

To improve our understanding of the processes of landfill leachate movement to, and degradation in, groundwater, and to identify the extent of existing and likely future groundwater contamination from UK landfills, in order to inform their design and sustainable management.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of tools for assessment of risk to groundwater from landfill and to inform the design and management of landfill sites under different hydrogeological conditions	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• building on the 1991 review of landfill monitoring in England and Wales, to identify the extent of groundwater contamination by landfill	£	S
• leachate transport and attenuation and degradation in UK aquifers	££	M
• biogeochemical processes in aquifers and the influence of a cocktail of contaminants	££	S
• the importance of preferential flow in relation to the contamination of minor aquifers by landfills (especially in Scotland)	££	M
• development of techniques and/or instrumentation for: the early detection of leaks, remote leachate monitoring and for effective drainage blankets	££	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Unsaturated Flow and Transport	Saturated Flow and Transport
Reactive Transport	
Fracture Flow	
Microbiological Processes	
Gas Exchange	

Key:

Beneficiaries/funders		*Annual cost*	*Time*
C - Water Utilities	I - Industry & Users	£ - Low	S - Short
E - Environmental NGOs	R -Regulators	££ -Moderate	M - Medium
G - Government	N - Research Councils	£££ - High	L - Long

TABLE 8.5

LAND USE CHANGE

Beneficiaries: G,R,E,N

RESEARCH OBJECTIVES

To improve the understanding and prediction of the impacts on groundwater resources and quality of different urban and rural land use changes, including the application of modelling and mapping tools, thereby facilitating sustainable groundwater management.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of predictive models of the consequences of land use change for groundwater quality and quantity	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• evaluate the consequences of the spread of the 'built' environment on groundwater resources and quality	£	M
• improved digital databases for critical hydrogeological and hydrogeochemical parameters of different aquifers	£	S
• improved models for estimating the effect of land use change on groundwater recharge and quality	£	S
• improvement of coupled, surface water and groundwater models	£	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Soil Processes	Unsaturated Flow and Transport Reactive Transport

Key: *Beneficiaries/funders* C - Water Utilities, E - Environmental NGOs, G - Government, I - Industry & Users, R -Regulators, N - Research Councils; *Annual cost* £ - Low, ££ -Moderate, £££ - High; *Time* S - Short, M - Medium, L - Long

TABLE 8.6

LOW FLOWS

Beneficiaries: C,R,E,N

RESEARCH OBJECTIVES

To improve our understanding of the interaction between groundwater and stream low flows under different hydrogeological, geomorphological and meteorological conditions, in order to develop groundwater management strategies for limiting environmental damage and optimising groundwater abstraction.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• develop predictive management tools for estimating and reducing the impact of groundwater abstraction on low flows under different conditions, including appropriate cost-benefit methodology	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• development of consistent approach to coupling of operational hydrological models with time series and spatial databases in relation to impacts of low flows	£	S
• improved understanding of relationship and nature of surface water-groundwater interactions, including improved understanding of valley bottom hydrogeology and impacts of groundwater abstraction	££	M
• use of GIS to integrate soils, hydrogeology, land use, topography and climate data so as to improve low flow predictions	££	M
• development of low-flow forecasting models	££	S
• improved understanding of the impact of changing low flows on freshwater ecology	£	M
• establishment of a site(s) for low flow studies	££	L
• evaluation of impacts of other processes on low flows, including land use and drainage, through establishing linkages to other research	£	M

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Unsaturated Flow and Transport Saturated Flow and Transport	Soil Processes Fracture Flow

Key: *Beneficiaries/funders* C - Water Utilities, E - Environmental NGOs, G - Government, I - Industry & Users, R -Regulators, N - Research Councils; *Annual cost* £ - Low, ££ -Moderate, £££ - High; *Time* S - Short, M - Medium, L - Long

TABLE 8.7

NAPLs

Beneficiaries: C,R,I,E

RESEARCH OBJECTIVES

To improve our understanding of the transport and fate of NAPLs in groundwater and of the extent of present contamination of UK groundwaters to enable risk assessment, quality prediction and the design of mitigating actions to ensure compliance with water quality standards.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• define techniques and strategies for delimiting, for source control and for containment, NAPL spills and define optimal methods for remediation under different hydrogeological and contaminant conditions	££	L

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• laboratory studies to investigate fundamental processes of DNAPL migration followed by verification at the field scale	££	M
• assess the importance of preferential flow	£	M
• practical use of multiphase flow models (including the vapour phase) including parameter identification and aquifer characterisation	£	M
• development of rapid methods for delineation of contaminated zones by surface geophysics and vapour surveys	£	S
• develop methods for the estimation of residual saturation in aquifers	£	S
• interaction and passage of NAPLs through aquitards	£	M

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Saturated Flow and Transport	Unsaturated Flow and Transport
Fracture Flow	Microbiological Processes
Multiphase Flow	
Gas Exchange	

Key: *Beneficiaries/funders* C - Water Utilities; E - Environmental NGOs; G - Government; I - Industry & Users; R -Regulators; N - Research Councils. *Annual cost* £ - Low; ££ -Moderate; £££ - High. *Time* S - Short; M - Medium; L - Long

TABLE 8.8

NITRATE

Beneficiaries: C,R,I,E,G

RESEARCH OBJECTIVES

To improve our understanding of the processes affecting the concentrations (and probable long-term decline) of nitrate in groundwater in order to improve prediction of future water quality and thereby ensure compliance at groundwater sources.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• further refine existing nitrate management strategies through improved predictive modelling of nitrate transport and behaviour in the unsaturated and saturated zones of aquifers	££	S

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• examine and quantify the processes of denitrification in aquifers	£	S
• analyse the effectiveness of artificial-recharge as a strategy for the treatment of high nitrate groundwater	££	M
• assess the importance of preferential flow in the transport of nitrate in both the unsaturated and saturated zones	££	M
• improve understanding of downward leaching of nitrate from particular soil/crops systems	££	M
• better understanding of post-drought variations in nitrate concentrations	£	M
• characterisation of non-agricultural sources of nitrate in groundwater	£	M
• assess the effect of changes in agricultural practices using nitrate records	£	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Soil Processes	Unsaturated Flow and Transport
Saturated Flow and Transport	Reactive Transport
Microbiological Processes	Fracture Flow
	Gas Exchange

Key: *Beneficiaries/funders* C - Water Utilities; E - Environmental NGOs; G - Government; I - Industry & Users; R -Regulators; N - Research Councils. *Annual cost* £ - Low; ££ -Moderate; £££ - High. *Time* S - Short; M - Medium; L - Long

TABLE 8.9

PESTICIDES

Beneficiaries: C,R,E,I,G,N

RESEARCH OBJECTIVES

To improve our understanding of the transport and fate of pesticides in groundwater and the extent of present contamination of UK groundwaters to enable risk assessment, quality prediction and the design of mitigating actions to ensure compliance with water quality standards.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of risk assessment methods and catchment management strategies	££	S

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• pesticide degradation in the unsaturated and saturated zones	££	M
• modelling of pesticide transport from the soil zone	£	S
• studies of the behaviour of combinations of pesticides and the influence of dissolved organic carbon and nutrients	££	M
• studies of the effect and behaviour of formulation products and metabolites	££	M
• quantify the importance of preferential flow	££	M
• baseline survey from unsaturated zone profiles and observation boreholes	££	L
• improve analytical and assay techniques	£	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Soil Processes	
Unsaturated Flow and Transport	
Saturated Flow and Transport	
Reactive Transport	
Microbiological Processes	
Fracture Flow	

Key:	*Beneficiaries/funders*		*Annual cost*	*Time*
	C - Water Utilities	I - Industry & Users	£ - Low	S - Short
	E - Environmental NGOs	R -Regulators	££ -Moderate	M - Medium
	G - Government	N - Research Councils	£££ - High	L - Long

TABLE 8.10

REMEDIATION

Beneficiaries: C,I,R

RESEARCH OBJECTIVES

To analyse the coupled physical and chemical processes involved in contaminant remediation and to develop monitoring technologies allowing the identification of a menu of cost-effective remediation options under different hydrogeological conditions and for different pollution incidents.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• improve the monitoring and modelling of remediation activities and evaluate their effectiveness	£	M
• develop risk assessment and decision support systems for designing cost-effective remediation strategies	£	S

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• develop and improve remediation methods, including enhanced bioremediation	££	M
• analyse the effectiveness of different remediation strategies at a site(s)	££	L
• further development of instrumentation for monitoring purposes	££	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Reactive Transport	Soil Processes
Microbiological Processes	Unsaturated flow and Transport
Fracture Flow	Saturated Flow and Transport
	Multiphase Flow

Key:	*Beneficiaries/funders*		*Annual cost*	*Time*
	C - Water Utilities	I - Industry & Users	£ - Low	S - Short
	E - Environmental NGOs	R -Regulators	££ -Moderate	M - Medium
	G - Government	N - Research Councils	£££ - High	L - Long

TABLE 8.11

VULNERABILITY

Beneficiaries: R,C,I,E

RESEARCH OBJECTIVES

To improve our understanding of the processes which attenuate pollutants, especially within soil and any superficial cover, and thereby to identify the risk to underlying aquifers, enabling optimal and defensible land use zoning in areas of significant vulnerability.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of management tools to reduce pollution risk to vulnerable groundwater sources without unnecessary limits to economic activity	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• classification of potentially polluting activities with respect to groundwater, based on risk assessment studies	£	S
• identification of critical physical, chemical and biological factors controlling the transport of different classes of pollutants as a function of soil and geological conditions	££	M
• development of appropriate predictive transport models	£	M

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Soil Processes	Unsaturated Flow and Transport
Reactive Transport	Saturated Flow and Transport
Fracture Flow	Microbiological Processes
	Multiphase Flow

Key: *Beneficiaries/funders*
C - Water Utilities
E - Environmental NGOs
G - Government
I - Industry & Users
R -Regulators
N - Research Councils

Annual cost
£ - Low
££ -Moderate
£££ - High

Time
S - Short
M - Medium
L - Long

TABLE 8.12

SOURCE PROTECTION

Beneficiaries: C,R

RESEARCH OBJECTIVES

To develop further our understanding of groundwater flow and transport to groundwater supply sources to allow source protection without unduly restricting land use, strengthening the wide applicability, objectivity and defensibility of existing approaches.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• assessment of the degree of confidence in the methods used for defining protection zones for specific aquifers taking into account parameter uncertainty and aquifer variability by, *inter alia*, refining the national approach to the definition of source protection zones	£	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• the significance of transient aquifer behaviour as a result of recharge variations when using steady-state models	£	S
• the review of long, thin protection zones for small abstractions in low porosity aquifers and the further development of methodology if required	£	S
• assessment of the general validity and usefulness of the modelling approach in predominately fractured or karstic aquifers or where adits are used to collect water, reviewing the usefulness of protection zones in these cases and further developing methodology if required	££	M

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Unsaturated Flow and Transport	Soil Processes
Saturated Flow and Transport	Multiphase Flow
Reactive Transport	
Fracture Flow	

Key: *Beneficiaries/funders*
C - Water Utilities
E - Environmental NGOs
G - Government
I - Industry & Users
R -Regulators
N - Research Councils

Annual cost
£ - Low
££ -Moderate
£££ - High

Time
S - Short
M - Medium
L - Long

TABLE 8.13

SUSTAINABLE YIELD

Beneficiaries: C,R

RESEARCH OBJECTIVES

To improve our understanding of the processes affecting groundwater recharge and storage in different hydrogeological environments in order to enable sustainable groundwater management and rational abstraction licensing.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of groundwater management tools to facilitate rational abstraction licensing based on defensible estimates of sustainable groundwater resources, with acceptable environmental impacts	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• in-depth review of operational experience	£	S
• importance of the unsaturated zone for drought storage	££	M
• development of stochastic water resource models	£	M
• estimating the spatial variability of recharge	£	M
• storage in drift and leaky aquitards	££	M

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Unsaturated Flow and Transport Fracture Flow	Saturated Flow and Transport

Key:

Beneficiaries/funders		*Annual cost*	*Time*
C - Water Utilities	I - Industry & Users	£ - Low	S - Short
E - Environmental NGOs	R -Regulators	££ -Moderate	M - Medium
G - Government	N - Research Councils	£££ - High	L - Long

TABLE 8.14

WETLAND CONSERVATION

Beneficiaries: E,R,N

RESEARCH OBJECTIVES

To improve our understanding of the interaction between groundwater and surface water in wetlands, to allow assessment of the impact of groundwater abstraction on water levels in wetlands, and of changing groundwater quality, and to guide sustainable groundwater and wetland management.

OPERATIONAL RESEARCH REQUIREMENTS	Cost	Time
• development of tools and management models for the prediction of the impact of groundwater abstraction and variations in groundwater quality on wetland ecosystems	££	M

APPLIED RESEARCH & DATA REQUIREMENTS	Cost	Time
• strategic monitoring of wetlands	££	L
• assessment of the hydraulic properties of wetland soils and the processes of groundwater movement within the shallow saturated zone	££	M
• analysis of surface water-groundwater interaction, and an improved understanding of valley bottom wetland hydrogeology	££	M
• establish the relationship between flows of water within wetlands and the spatial and temporal variations in water quality	££	L
• develop ways of classifying the vulnerability of wetlands	£	S

HYDROGEOLOGICAL PROCESSES

Major	*Minor*
Soil Processes Saturated Flow and Transport	Unsaturated Flow and Transport Fracture Flow

Key:

Beneficiaries/funders		*Annual cost*	*Time*
C - Water Utilities	I - Industry & Users	£ - Low	S - Short
E - Environmental NGOs	R -Regulators	££ -Moderate	M - Medium
G - Government	N - Research Councils	£££ - High	L - Long

Operational research overview

Box 8.2 summarises the operational research requirements for the priority issues, drawing from each of Tables 8.1. to 8.14. This is an important list of activities needed to provide the managers and developers of UK groundwater resources with the information and tools they need and currently lack.

BOX 8.2 Issue-specific Operational Research Requirements

ISSUE	OPERATIONAL RESEARCH REQUIREMENTS
Acid Mine Drainage	develop predictive tools for assessing the impact of mine/minefield closure and the subsequent pumping regime on groundwater quality in adjacent aquifers and on the seepage of acidic mine waters to surface water courses including scale and longevity, and then formulation of abandoned mine/minefield protocols and groundwater management strategies for the mitigation of AMD on groundwater
Afforestation	develop predictive tools to assess the impact of afforestation on groundwater quality and quantity and determine appropriate forest and groundwater management strategies
Contaminated Land	develop tools to assess risk to groundwater sources and management strategies to identify and implement economic and effective mitigation actions
Landfill	develop tools for assessment of risk to groundwater from landfill and to inform the design and management of landfill sites under different hydrogeological conditions
Land-use Change	develop predictive models of the consequences of land use change for groundwater quality and quantity
Low Flows	develop predictive management tools for estimating and reducing the impact of groundwater abstraction on low flows under different conditions
NAPLs	define techniques and strategies for delimiting, for source control and for containment of NAPL spills and for predicting eventual concentrations at supply sources and define optimal methods for remediation under different hydrogeological and contaminant conditions
Nitrate	refine nitrate management strategies through improved predictive modelling of nitrate transport and behaviour in the unsaturated and saturated zones of aquifers and eventual concentrations at supply sources
Pesticides	develop risk assessment methods and catchment management strategies and tools to predict eventual concentrations at supply sources
Remediation	improve the monitoring and modelling of remediation activities and evaluate their effectiveness; develop risk assessment and decision support systems for designing cost-effective remediation strategies
Vulnerability	develop management tools to reduce pollution risk to vulnerable groundwater sources without unnecessary limits to economic activity
Source Protection	assessment of the degree of confidence in the methods used for defining protection zones for specific aquifers taking into account parameter uncertainty and aquifer variability by, *inter alia*, refining the national approach to the definition of source protection zones
Sustainable Yield	develop groundwater management tools to facilitate rational abstraction licensing based on defensible estimates of sustainable groundwater resources, with acceptable environmental impacts
Wetland Conservation	develop tools and management models for the prediction of the impact of groundwater abstraction and variations in groundwater quality on wetland ecosystems

Reviewing Box 8.2 allows the distilling of three main areas for generic operational research; detailed in Box 8.3 and summarised as follows:

- developing predictive tools and risk assessment procedures for assessing the impact of human activities *(managing the future);*
- developing or further refining tools for sustainable groundwater management *(managing the present);* and
- developing or further refining mitigation and remediation strategies *(managing the past).*

Thus risk assessment, management and remediation are the major areas for operational research. The subject of *risk assessment*, which came up extensively in the consultation exercise as a major gap needing to be filled, is addressed in Chapter 11.

BOX 8.3 Generic Operational Research Requirements

1. Develop predictive tools and risk assessment techniques for assessing the impact of:
   - groundwater abstraction on low flows and wetlands;
   - nitrate and pesticide application, transport and degradation on quality, particularly at groundwater supply sources;
   - landfill, contaminated land, and NAPL splills on groundwater quality, particularly at supply sources;
   - mine/minefield closure on groundwater and surface water quality;
   - afforestation and other urban and rural land-use change on groundwater quantity and quality.
2. Develop/further refine tools for sustainable groundwater management (guidelines, protocols, strategies, models, decision support systems, etc.) to take special account of:
   - overall resource protection from pollution, at catchment scale, particularly of vulnerable areas;
   - defensible source protection, particularly in complex hydrogeological conditions;
   - stream and wetland ecosystem protection;
   - borehole abstraction licensing;
   - urban and rural planning and land use, including forest management;
   - abandoned mine and minefield management;
   - landfill management.
3. Develop/further refine mitigation strategies for:
   - contaminated land
   - NAPL spills;
   - balancing peak demands and low flows;
   - high nitrate and pesticide legacy levels.

Applied research overview

The applied research topics identified above (especially Tables 8.1 to 8.14) illustrate the wide range of research required. Most topics require some form of assessment of the scale of the 'problem' usually by reviewing existing data. This is followed by an identification of the principal underlying processes which can explain the observations at least in a qualitative sense. Finally, a model is often produced which explains in a quantitative way the observations and enables predictions about future behaviour to be made. The sophistication of such models can vary enormously: sometimes only a very simple model can be justified given the known uncertainties. In other cases, the basic underlying processes are sufficiently well understood to justify a more sophisticated approach. The aim of research is often to understand the issue sufficiently well at one or a few sites so as to be able to make predictions for other sites or other times. There is also an increasing need to be able to say how good (or bad) such predictions are likely to be.

Since the range of skills required for modelling are quite different from those required for acquiring field observations, an important part of larger research programmes is to facilitate the building up of research teams capable of tackling the complex issues involved in a balanced way. Observers must collect the data required for the models, and modellers must address the issues revealed by the data. Sometimes the way forward is not obvious: perhaps some fundamental problem must be solved before significant progress can be made. Other times new opportunities arise because of progress in allied fields, for example in monitoring technology, in computers or in our theoretical understanding of the issue. It is important to realise that many of the problems for which solutions are required are inherently very complicated.

Several recurring themes emerge in reading the lists of *Applied Research & Data Requirements*: the importance of preferential flow in UK aquifers and a continuing need to devise methods for quantifying its role in recharge and solute transport; the need to develop, apply and test models for reactive transport through aquifers; and the importance of linking together processes taking place in the unsaturated and saturated zones in a self-consistent way.

A broader recurring theme in groundwater research is the difficulty of building up an accurate three-dimensional picture of most aquifers. Observation boreholes are often few and far between (in relation to the spatial variability), and may not be ideally completed for the new types of observations demanded of them. The increasing importance of groundwater quality in recent years has raised new issues that both serve to complicate and constrain our understanding of aquifers. For example, observations of water quality stratification in aquifers reveal the complexity of aquifers but also help to define the flow paths.

An overall theme is one of uncertainty, and an important area of applied research is that of *managing groundwater under conditions of uncertainty*. Together with risk assessment, these emerging areas for research are covered in more detail below.

Hydrogeological Processes research overview

Hydrogeological Processes, as defined in this Study, are represented by important components in Box 7.2. Research on these processes underpins applied research work on all the issues in some way or another. Yet it is in this area of strategic research that research commissioners rarely perceive a responsibility or have an interest. While NERC has traditionally put funding into this area through its Special Topics and Community Programmes, the increasing pressure to be seen to focus more explicitly on 'wealth creation and quality of life' risks marginalising process research even further. The importance of this area of research is strongly emphasised. Without substantial effort to continue to learn more about hydrogeological processes, it will be impossible to advance the state of the art of groundwater management in the UK. However, it is very often possible to couple generic process research with much more applied work; for example a water company's concern over the risks presented by rapid transport of *Cryptosporidia* in the Permo-Triassic sandstones might readily match a research institute's interest in fracture flow, and the application of tracers would then provide mutually valuable information to meet both sets of demands.

In Box 8.4 an attempt is made to identify priority research within each of the Hydrogeological Process areas, based on the previously identified operational and applied research needs (derived from the priority issues). Also taken into consideration were the views expressed at the *Science Seminar*, where both the applied agenda as well as the underpinning agenda were considered.

Box 8.4. Priority Research Topics in Hydrogeological Processes Arranged in Order of Decreasing Priority

HYDROGEOLOGICAL PROCESS	PRIORITY RESEARCH TOPICS
Soil processes	Pollutant transport in structured soils. Nitrate leaching with emphasis on soils treated with organic waste. Pesticide degradation and leaching.
Unsaturated flow & transport	DNAPL migration (inc. estimation of residual saturation). Estimation of the importance of delayed recharge. Field scale models of transport (inc. transfer functions).
Saturated flow properties	Determination of the 3-D distribution of aquifer & transport (inc. aquitards and making use of geostatistical techniques). Understanding basic transport properties via tracer testing. Interaction between streams and aquifers. Carefully executed, monitored and analysed pumping tests.
Reactive transport	General-purpose coupled flow and reaction modelling.
Microbiology	Development of conceptual and mathematical models. Biodegradation in clean-up. Laboratory studies of pollutant degradation under simulated aquifer conditions.
Fracture flow	Use of novel techniques for characterising fractures and fracture networks (especially hydraulically active fractures).Validation of models against tracer test data and pollution monitoring data. Laboratory experiments to build a conceptual understanding of NAPL transport in fractures.
Multiphase flow	Development of conceptual and mathematical models of flow in the unsaturated zone and in fractures (above). Understanding controls on residual saturation.
Gas exchange	Gas fluxes through aquitards. Gas diffusion in aquifer rocks.

Brief summary of current research

EC - funded European research. In order to see how EC research funding relates to the needs identified in this Study, a search was carried out on the CORDIS RTD-Projects database. CORDIS (Community Research and Development Information Service) provides information about European Community Research and Technological Development (RTD) programmes. The search revealed 91 groundwater-related projects which are either completed or on-going. About 85% of the projects could reasonably be assigned to issues discussed in this Report: the remainder were either highly generic or related to issues not identified in this Study. The results are shown in Box 8.5. One third of all the EC-funded groundwater projects were related to radioactive waste disposal. Only about half of the issues identified in this Study are directly addressed by any of the projects, although three-quarters of the priority issues were addressed to some extent.

UK Research. There is no single directory of all current UK groundwater research. Groundwater research is carried out by universities, colleges, research institutes and centres, and by consultants. The most comprehensive source of information is contained in the 'Current Research in Britain' (CRIB) directory which includes research being carried out by over 400 universities, colleges and other institutions within the UK. Entries are based on voluntary contributions. The database lists research topics by institution, principal investigator, funder and duration. It does not include information about the value of the contracts and it does not include research being carried out by industry or by consultants. For example, the Water Research Centre is not included. The entries are updated annually. This was last carried out between February and May 1994. The latest CD-ROM version of this database was searched, using 'Groundwater' as the search term. A total of 91 entries were retrieved based on the contributions of 62 different researchers. Thirty-three of the entries could be directly related to 16 specific issues identified in this Study (Box 8.6) of which Radioactive Waste and Contaminated Land featured most frequently. Many of the other entries covered generic topics (eg Groundwater flow modelling and software development) or were more directly related to processes (eg Sulphur and sulphate oxygen isotope ratios of UK groundwaters). Some of the research was being carried out overseas (particularly that funded by ODA). A large number of funding agencies were involved in supporting this research. The major contributors were the Research Councils, universities, industry, ODA and the NRA (Box 8.7).

It is clear from the searches of European and UK research that there is a substantial programme of work under way (although it is significantly biased towards radioactive waste disposal). In preparing any proposal for groundwater research, it will be important to identify recent or ongoing research on the subject, in order to maximise effectiveness and value for money. It may be possible to seek partnerships, particularly in Europe, where this is encouraged by EC funding.

BOX 8.6 Number of Groundwater-related Entries in the 1994 CRIB Database (*indicates priority issues)

ISSUE	COUNT
Afforestation *	1
Borehole efficiency	1
Climate change	1
Contaminated land *	4
Microbiological contamination	2
Nitrate *	3
Non-aqueous phase liquids *	1
Radioactive waste disposal	6
Radon etc	1
Remediation *	1
Rising water levels	3
Sewers etc	1
Source protection *	2
Sustainable yield *	3
Vulnerability*	1
Wetland conservation *	2

BOX 8.7 Number of Entries in the 1994 CRIB Database Classified According to Funding Agency. Some of the Entries were Co-funded by Two or More Organisations

FUNDER	COUNT
NERC/SERC/AFRC/BMNH	26
University	16
Industry/CIRIA/BNFL	12
ODA	11
NRA	9
EC/ESF	7
MAFF/DoE	5
Overseas source	6
Water Utilities	3
Other	2

BOX 8.5 Number of CEC projects which address identified issues (* indicates priority issue)

ISSUE	COUNT
Acidic deposition	5
Afforestation *	1
Climate change	1
Contaminated land *	3
Deep waste disposal	1
Heavy metals	4
Landfill *	9
NAPLs *	1
Nitrate *	7
Pesticides *	5
Radioactive waste disposal	29
Radon etc	3
Remediation/clean-up technology *	2
Resource protection & vulnerability *	2
Saline intrusion	1
Source protection *	1
Wetland conservation	2

9. Research tools

Introduction

Key Research Tools, listed in Box 9.1, are now briefly discussed. Some combination of one or more of these tools is invariably a prerequisite for any research on groundwater. In addition, the tools themselves are subject to continuous refinement through research.

BOX 9.1 Research Tools

- Monitoring
- Survey
- Field experiments
  - Research sites
  - Tracer tests
  - Pumping tests
- Laboratories and laboratory experiments
- Modelling
- Measurement technology
- Databasing and other information technology

Monitoring

Monitoring is an important activity which provides many operational and, often, strategic returns. While the case for monitoring is invariably made on the grounds of operational need (and increasingly on compliance grounds), there are very significant returns to the R&D agenda, as good time series data will serve many R&D requirements. There is thus a rarely recognised financial return: monitoring will reduce the cost and increase the effectiveness of an R&D programme. This variety of benefits, however, brings with it the difficulty of setting criteria for network design: it is extremely difficult to quantify the 'value' of data, except in unusually simple circumstances. It is therefore almost impossible to justify strategic monitoring, on a cost-benefit basis, although any reduction in monitoring density (spatially or temporally) should not be undertaken lightly.

The NRA is currently examining the questions of water level and water quality monitoring. Water level data collection presents few technical difficulties and coverage is generally considered to be adequate. However, there is a particular need to monitor in and around wetlands and other environmentally sensitive areas. Rising water levels, both in abandoned mines and beneath cities, also require monitoring. The collection of water quality data is a much more recent activity which has attracted limited funding due to the general lack of resources when the need became most apparent during the 1980s.

At the same time, the existence of large data sets and their continued collection by various agencies needs to be recognised. For example, county council waste regulation authorities hold water quality and water level data from landfill sites, generally on public register.

There is a very strong need for 'smart' detectors (eg to 'watch out for' a variety of pesticides concurrently). Clean-up exercises also require careful monitoring. Long-term monitoring of pollution undoubtedly has a high strategic value. Technological advances are bound to be of significant help; for example improved communications technology can be expected significantly to reduce monitoring costs in just a few years.

Survey

Survey is distinguished from monitoring (above) although the former often depends on the latter. 'Survey' here refers to an areal, at least partly field-based, investigation. In many areas related information will have been collected by different organisations and would profit from being collated and studied as a whole. Sometimes different types of information will be available for the same region or aquifer or source: sometimes the same type of information will be available for different regions, aquifers or sources. There are several specific survey needs. For example, a particular need is to establish the extent of groundwater pollution from historic landfill, contaminated land and pesticides. Maintaining a national survey programme will allow gathering, distilling, compiling and disseminating information which will lower the costs of research as well as of groundwater management and development.

Field experiments

Hydrogeological fieldwork is expensive. A single funder concerned with a specific issue will often be unwilling to fund field experiments to the extent required for significant progress. This situation is one of growing concern. Many younger researchers (say under 35 years) in the UK have never experienced working at a significant research site, as insufficient funding has been available for field experiments over the last ten years. As a

BOX 9.2 The Case for National Groundwater Research Sites

POSSIBLE BENEFITS

- The ability to address several issues at one site
- Consequent major economies of scale and shared infrastructure
- The ability to work in well-characterised environments
- The excellent training environment created for young researchers and for groundwater professionals
- A framework for the development of operational and research tools

POSSIBLE DRAWBACKS

- Problem of extrapolation to other areas
- Any site chosen for multiple research interests may not be the best site for any one of them
- Requires extensive use to reduce the proportion of fixed costs to research costs

BOX 9.3 Opportunities Provided for Groundwater Research by Different Types of Site and by Specific Site Investigations (site types arranged in alphabetical order; important issues in upper case)

TYPE OF SITE	PRIORITY ISSUES	OTHER ISSUES	ACTIVITIES
Clean-up	REMEDIATION CONTAMINATED LAND NAPLS		'Opportunistic'. Monitor and analyse effectiveness of an on going programme. Tracer tests.
Contaminated land	CONTAMINATED LAND LANDFILL NAPLs REMEDIATION	Heavy metals	Development of techniques for characterising extent and nature of groundwater contamination, and modelling its migration.
Landfill	LANDFILL NAPLs	Subsurface methane Rising water levels Heavy metals	Mostly monitoring and geotechnical. Very complicated.
Lysimeter	LAND-USE CHANGE NITRATE RESOURCE PROTECTION & VULNERABILITY PESTICIDES NAPLs SUSTAINABLE YIELD	Acidification Microbiological contamination	Possible single, large lysimeter (expensive) or scattered and small (less useful). Test transport under near-natural conditions. Tracer tests
Mine	ACID MINE DRAINAGE CONTAMINATED LAND	Rising water levels Geochemical baseline change Heavy metals Saline intrusion Subsurface methane	Detailed monitoring and modelling required. Unrelated to most other hydrogeological issues.
Small sources	SOURCE PROTECTION SUSTAINABLE YIELD RESOURCE PROTECTION & VULNERABILITY	Radon, radium and uranium Unregulated Rural Supplies	Likely to be very variable. More suitable for survey than detailed investigation.
Stream/aquifer interaction	LOW FLOWS AFFORESTATION LAND-USE CHANGE NITRATE PESTICIDES RESOURCE PROTECTION & VULNERABILITY SOURCE PROTECTION SUSTAINABLE YIELD	Quarrying	Small agricultural catchment required. Chalk or Permo-Triassic sandstones. Possibly near a borehole (induced recharge).
Test boreholes	SOURCE PROTECTION SUSTAINABLE YIELD	Borehole efficiency	Development of tracer test methodology, develop pumping test methodology and analysis. Evaluate 3-D permeability distribution. Use and development of geophysical techniques
Wetland	WETLAND CONSERVATION SUSTAINABLE YIELD	Climate change	Mostly strategic monitoring.

consequence, there is very limited gathering of new data. Important research tools that fall within the category of field experiments include tracer tests and pumping tests.

Research sites. Despite much discussion over recent years, the research community has had little success in establishing national groundwater research sites. The possible benefits and drawbacks of communal research sites are given in Box 9.2. Research sites can vary in size from lysimeters or boreholes to fields or catchments. Important research opportunities exist at specific site investigations, such as those undertaken by industry generally ('opportunistic' research). Various types of site are considered in Box 9.3 which shows the issues which can be addressed with each. Also indicated are some of the activities that could be undertaken at the research sites. Both conceptual and simulation modelling would be an integral part of each of these activities.

Selection of the groundwater research site location inevitably presents some difficulties. Factors that need to be considered include: geology, representativeness of the site, likely generic characteristics, accessibility and logistical convenience, assured tenancy, length of previous records and proximity to special hydrological features. A range of sites is required: for example, research on a Chalk site would not address problems relating to the Triassic sandstones.

In order to prioritise the type of sites to be studied, the following factors need to be considered: range and importance of issues that could be addressed, range of research and monitoring activities relevant to the site and the lack of suitable existing sites. Some sites would be predominantly used for monitoring, others would be primarily experimental and highly 'stressed' by the research activities. Several types of site could be combined within a single area or catchment to their mutual advantage. There is an important opportunistic element to the selection of research sites. For example, detailed investigations at a remediation site would provide support to the clean-up operation and would provide results of broader value for the hydrogeological community.

In terms of groundwater research sites, as opposed to 'opportunistic' site investigations, it is judged that the greatest return would be obtained from:

- *test borehole sites*: although these do not *directly* address the major issues, they provide an opportunity to investigate the basic hydrogeology and the underlying geological influences through the use of a wide variety of techniques.
- *stream-aquifer interaction sites*: while many catchments have been studied *hydrologically*, further detailed studies focusing on the hydrogeology are required.
- *lysimeters*: lysimeters can be used either to monitor natural behaviour or in an experimental mode to study flow and transport under carefully controlled conditions. There are very few lysimeters in operation in the UK. A particular benefit is the possibility of using tracers that may be unacceptable if allowed to drain to the water table.

Tracer tests. While rates of flow in groundwater can often be estimated with confidence, even when few site-specific field data are available, rates of pollutant transport can rarely be estimated. Part of the difficulty is that while the effects of heterogeneity of the subsurface are averaged out by flow (ie average parameter values suffice), that same heterogeneity has additive effects on transport, causing growing uncertainty over pollutant transport as distance of travel increases. In time our knowledge of the structure and variation within our aquifers will improve to a point where it will become possible to model transport with confidence. However, the time scale for that to come about is probably many decades and possibly centuries. In the meantime we need to build an approximate picture of pollutant transport in our aquifers, if we are to predict the movement of contaminants. A medium-term approach is to use 'tracers' to determine transport behaviour in aquifers directly, cutting across the complexities of the processes, aquifer parameters and heterogeneity. Tracers can be applied in well-controlled experiments but pollution itself provides a useful if unwelcome tracer - long-term monitoring of pollution migration is an important task that needs consideration wherever the opportunity arises. More could thus be done in terms of analysis of data from long-term pollution sites.

Pumping tests. Pumping tests are arguably the most widely practised and important technique in the hydrogeologist's toolbox. Such tests are carried out routinely; for example, when any significant borehole supply source is established. However, these tests are often poorly monitored so analysis of the results is difficult and frequently inconclusive; also, results are often not adequately reported. Thus,

BOX 9.4 Groundwater Modelling

Why model?	Hypothesis testing Policy comparison Development of regulations and policies Project focus Framework for balanced data collection/organisation Parameter estimation (often for use in other models)
Prerequisites:	Well-defined problem Conceptual understanding of groundwater system Mathematical formulation of important processes Parameter values Calibration/validation data
Modelling issues:	Use of proprietary codes Role of models in legal proceedings Role of model validation Effects of uncertainty and reporting of implications Need for QA Danger of modelling as substitute for other activities

despite significant investment, the results of many pumping tests are unusable. At the same time, relatively sophisticated tests are being carried out by British hydrogeologists; for example, working on development projects overseas and on radioactive waste disposal in the UK. There would be real benefits in carrying out carefully monitored pumping tests involving suites of piezometers (observation boreholes) and modern data analysis tools, in order to obtain less ambiguous test interpretations. In our major aquifers, the aim must be to understand flow in three dimensions and flow through both higher permeability features (especially fractures) and lower permeability aquitards.

Laboratories and laboratory experiments

Laboratories serve two principal functions. Firstly, in order to improve our understanding of groundwater processes, and to develop and test mathematical models which will describe them, it is usually necessary to begin with a range of relatively simple experiments carried out under well-controlled conditions. These experiments are best done in a laboratory and can often prove to be revealing. This is essentially the laboratory in its research role. Secondly, there are many standard physical, chemical and microbiological procedures which are routinely used for measuring various aquifer or groundwater properties. This is the analytical role. There are of course important areas where these two functions overlap, eg in the development and testing of new analytical methods.

Since the capital and maintenance costs of well-found laboratories are large, it is important that their resources are used efficiently, for example by sharing facilities or by buying-in outside services where appropriate. This tends to lead to some degree of specialisation both in research and analytical laboratories. Laboratories also require a skills base. For example, it has been estimated that it takes 15 years to train a skilled experimentalist. Nurturing well-found laboratories does not always sit comfortably with the use of market principles alone for commissioning laboratory work.

Specific topics that need to be addressed include laboratory studies of reactive transport through aquifer materials, transport and residual saturation characteristics of NAPLs, studies of the rate of degradation of pesticides under aquifer conditions and characterisation of aquifer matrix heterogeneity.

Modelling

Modelling consists of conceptual modelling, mathematical modelling, analytical modelling and numerical (computer) modelling. For many areas of hydrogeology the conceptual modelling is adequate and the only outstanding requirement is the development of practical user-friendly tools. However, in some areas even the correct conceptualisation remains to be completed. For example, multiphase flow in fractured media poses fundamental problems, and for many biochemical processes the equations are rudimentary, if they exist at all. The need in relation to addressing issues is often not for more modelling but for supporting work such as laboratory investigations.

There are now many groundwater modelling courses on offer and most environmental consultants offer groundwater modelling services. There is a great danger in regarding groundwater modelling tools in the same manner as common personal computer software. A good computer, the latest software and attendance at a modelling course for 5-10 days does not make a modeller. An eminent US modeller has suggested that ten years of experience is required to become skilled in the art of groundwater modelling.

Box 9.4 summarises the reasons for modelling, some of the prerequisites and some concerns.

Modelling has often outpaced our knowledge of groundwater systems and data availability. However, there remain model development needs in the general areas of: double-porosity flow and transport, multiphase flow (including unsaturated flow), coupled geochemistry and flow, and biochemistry. One specific need is in relation to source protection, particularly in fractured and karstic aquifers. Other specific needs include *stochastic* water resources models and wetland models. More generally, there is a need for rigorous validation of models against carefully collected field data.

Measurement technology

Hydrogeology has benefited from technological developments in other, better funded, R&D areas, such as hydrocarbon production. A watching brief needs to be kept on developments in those fields but hydrogeology-specific developments are also required. Promising developments appear to include continuous downhole monitoring tools, and geophysical tools (especially those based on tomographic methods). Specific needs that have been identified include: flux monitoring (in both the saturated and unsaturated zones), clean-up monitoring (especially for DNAPLs), and novel sensors, especially for pesticide assay.

Databasing and other information technology

Groundwater management has much to gain from strategic databasing and to some extent this is being undertaken. For example, a database of the hydrogeological properties of the major UK aquifers is currently being assembled (by the NRA and BGS). However, not all opportunities are being exploited. For example, results from

BOX 9.5 Decision Support System Components

A 'modelbase':	a variety of tools (most commonly predictive computer models)
A database:	data used in judgement (often including 'unofficial' information and linked to organisational databases)
A 'knowledge base';	information such as rules and regulations

pumping tests, tracer tests and other field experiments would provide a valuable source for model calibration and research. The roles of different institutions and the sources of funding need review.

Scientists produce data, knowledge and a variety of tools for using that data and knowledge. The form in which the results of R&D need to be presented depends to some extent on the way in which those results are to be used and therefore on the tools used in applying the results. These tools may take a simple form such as graphs, tables and rules-of-thumb; more recently computer-based tools have become prevalent: some of these major tools are discussed briefly below.

Expert systems are computer programs that aim to use knowledge and formal reasoning techniques to solve problems or give advice. Specialists will be involved in the development of these systems since it is necessary to provide *rules*, which may be derived from expert opinion or from more analytical techniques such as scoping studies with models. Although these systems undoubtedly have a role to play in the management of groundwater, they are currently treated with scepticism by groundwater specialists and managers alike, mainly due to the fact that they can never be better than the knowledge used in their development - often incomplete in the case of groundwater - and due to their implied role of taking decision making away from experts.

A decision support system (DSS) is an interactive computer-based system that helps decision makers utilise data and models in the solution of unstructured problems. There are various DSS 'architectures' but the main elements are indicated in Box 9.5. Such systems include information on the models in the modelbase which aids the choice of model. DSSs can provide a framework for initiating R&D work and for encapsulating its results. For example, a DSS can contain a model, the user-manual for that model, rules to help in the decision of whether or not to use the model and certain types of data associated with the model. Scientists therefore generally favour the use of such tools as they have the potential to make research results usable in a well-controlled framework.

A *geographical information system (GIS)* is a database management system that handles features that would normally be found on a map and presents them to the user in a graphical form on a computer monitor. Some confusion is possible over the role of a GIS, as attempts have and are being made to integrate tools, especially groundwater models, into GIS. This is an apparently attractive development but carries with it certain difficulties such as flexibility in upgrading. A role which GIS is certainly well suited for is as an *interface* to groundwater models, in particular as an element of decision support systems. As GIS development is encouraged by such a wide family of users, there is little if any need for further encouragement - at least not as far as generic systems are concerned. Caution needs to be exercised in encouraging the development of specific GIS systems dedicated to groundwater or even hydrological use.

10. Uncertainty and risk in groundwater management

Introduction

Throughout the process of consultation and the review of research needs, the subject of decision making under conditions of uncertainty and the separate but related subject of risk assessment and management came up time and again. A conclusion is drawn that these are extremely important areas for further analysis and for the development of effective principles and tools. Advances here will inform work across the whole R&D agenda and across operational practice in groundwater development and management.

Groundwater management practice, following the precautionary principle, will aim to ensure wide margins of safety when there is parameter uncertainty, and tools to reduce uncertainty will allow more sensitivity in decision making, with potentially major economic gains through greater confidence in more finely balanced decisions regarding groundwater quantity and quality controls.

Risk assessment and management in relation to groundwater can mean many different things: the risks to health and ecology from groundwater quality; the risk to ecology and related areas (including amenity, property values etc) from groundwater quantity; the risk to utility business from groundwater quantity and quality; and the risk to the financial markets from pollution liability or quantity/quality regulation. The primary focus of groundwater risk assessment relates to quality and impacts on health and ecology (and related investments in treatment). This is the subject of a brief discussion below. However, other areas are also important. For example, the City is playing a greater and greater role, explicitly and implicitly, in determining the direction of groundwater development, and considers groundwater-related environmental liabilities to be very threatening in the general inability to assess risk. As a consequence, risk avoidance is the preferred route, affecting industrial investments, land sales, insurance policies etc. The financial implications are enormous, particularly as the European Commission is proposing strict (no fault), joint and several (deep pocket), and retroactive (no time bar) liabilities for pollution losses.

Uncertainty: sources and approaches

One view of the whole R&D programme is that it should aim to quantify and reduce uncertainties to an extent that decision making is feasible, precise and accurate. There are a variety of sources of error in hydrogeological prediction, including: rock variability, measurement errors, conceptualisation errors, inadequate understanding of processes, inadequate models and unknown stresses on the groundwater system (eg pumping and future recharge). Measures that can be taken to evaluate, mitigate or remove these errors include improving scientific knowledge, appropriate use of hydrogeological tools and development and application of appropriate methodology.

Field data invariably suffer from uncertainty due to geological variability. Probability-based techniques (eg kriging) have been developed in recent years for dealing with this type of uncertainty. Much more needs to be known about the spatial variability of our soils, aquifers and aquitards before such techniques can be used effectively. Some development of the mathematical and computing techniques is also required but these have tended to lead the data collection significantly.

Model use should include *sensitivity analysis* and *uncertainty analysis*, which lead to better appreciation of the reliability of model results in relation to conceptualisation and parameter uncertainty. In some cases, the comparison of results from different conceptual models is advisable. Separate groups working with the same data will often produce quite different results and for critical work such comparative exercises can be very valuable. There is a need to establish a better appreciation of the validation process and the reliability of models; this might include legal considerations concerned with model use. Also, it may be prudent to develop and apply quality assurance procedures for model use, particularly in important circumstances.

Further improvements in all of these and other tools for handling uncertainty should be encouraged. Valuable experience has been gained in code comparison exercises in the radioactive waste field, where much greater investments are being made in groundwater-related research than anywhere else. This experience would provide lessons of general value to the groundwater community.

Role of risk analysis: the case of groundwater quality

The US National Academy of Sciences separated *risk assessment* from *risk management*, in order to encourage clarification of the boundaries between the technical and the scientific components of regulatory activities and the social, economic, and political pressures that constrain regulatory decision-making.

Environmental risk assessment is the characterisation of the potential adverse effects of exposure to environmental hazards. Risk assessments can include several elements: description of the potential effects on organisms based on toxicological, epidemiological, and ecological research; extrapolation from those results to predict the type and estimate the severity and extent of effects in natural populations under given conditions of exposure; estimation

BOX 10.1 A Role for Risk Analysis in Groundwater Management?

- Should risk assessment be more widely practised in order to decide priorities in groundwater management and investigations and thus improve cost-effectiveness?
- Is risk assessment the proper basis for regulatory decisions? If not, is it an important element in formulating those decisions? Under what circumstances might a 'risk-averse' approach be appropriate?
- Should groundwater investigations more routinely take account of the needs of risk assessment in the range of factors investigated and in the manner that results are presented?
- Do inherent problems in the philosophy and methodology of risk assessment significantly reduce its value for groundwater management?

of the species and locations of organisms exposed at various intensities and durations; and summary judgements on the existence and magnitude of the ecological problem. The process includes both quantitative risk assessment, with its reliance on numerical results, and qualitative expressions or judgements involved in the evaluation of the uncertainties inherent in generalised exposure analyses and laboratory-to-field extrapolation of toxicological studies.

Risk management is the process of evaluating alternative regulatory actions and selecting among them. Environmental risk management is the decision-making process that entails consideration of political, social, economic, and engineering information to develop, analyse, and compare possible regulatory responses to a potential ecotoxicological hazard. The selection process necessarily requires the use of value judgements on such issues as the acceptability of risk and the reasonableness of the costs of controls.

Risk assessment can be divided into four major steps: hazard identification, dose-response assessment, exposure assessment, and risk characterisation. A risk assessment may stop with the first step, hazard identification, if no adverse effects are found or if an environment agency elects to take regulatory action without further analysis, for reasons of policy or statutory mandate.

The *regulatory context* is changing as pressures grow for adopting risk as a basis for groundwater management. The word 'risk' now appears in EC Directives (eg in relation to the *Precautionary Principle*). Risk analysis software continues to be developed and is becoming more widely used. The recognition that any predictions of groundwater behaviour are subject to significant uncertainties naturally leads to a probabilistic treatment, which naturally leads on to risk analysis. The US National Academy of Sciences developed an analysis of risk assessment in regulatory agencies that has since been adopted by the US EPA as its standard approach to chemical safety issues. It is inevitable that environmental legislation will increasingly be framed around the concept of risk. There is growing concern amongst financial and industrial organisations regarding their liability for environmental and health damage. The insurance industry, being unable in many cases to assess risks and costs, is tending to retreat from environmental risk cover.

The application of risk analysis to groundwater in the UK has been limited, as it has been elsewhere. The general problem of risk assessment in groundwater contamination has been surveyed by the International Commission on Groundwater's 'Working Group on Groundwater Contamination Risk Assessment'. Their emphasis was on the management of health risks in the face of uncertainty.

Inability routinely to detect chemicals at levels suspected of having long-term chronic effects limits the ability to assess their risks. Rather than consider long-term optimisation of the performance of a system, the risk-averse approach attempts to derive operating policies which will minimise the worst possible 'failure' of the system. Risk-averse policies aim to avoid any possible damage, at the expense of good average performance. Unless levels of parameter uncertainty are reduced, it is possible that certain problems in groundwater management will be subject to this approach, which is potentially costly and, of course, inconsistent with 'cost-effective' and 'value for money' philosophies.

Risks analysis software is readily available for many scenarios and new packages appear regularly. When this software is used (as will occur more frequently) regulatory agencies need to have a view on the validity of the assumptions underlying the analysis and the database used. The regulators may choose to prescribe the use of certain packages.

Risk analysis relates to modelling in several ways. Models are important tools in the evaluation of the 'exposure function' which converts the source of risk into the 'dose' (eg mass of pollutant) contacted by an individual or the environment. If the output of a model is to be used as input to a formal risk-analysis procedure, that output must take a suitable form. Modelling carries with it the (internal) risk of producing incorrect results.

There is a danger that safety precautions increase the exposure to risk (the 'risk compensatory hypothesis'). For example, it must be considered possible that the groundwater protection policy could lead to an unjustified sense of security in the handling of chemicals in regions that do not fall within protection zones.

According to Jasanoff: "Recent judicial decisions in the area of risk management provide numerous examples of faulty scientific analysis by courts untrained in the intricacies of risk

BOX 10.2 Systematic Approach to Risk Assessment of Contaminated Groundwater

- Flexible approach to assessment of groundwater contamination in the particular circumstances.
- Quantitative measures of the effects of pollution.
- Procedures for identifying data needed to assess effects of contamination and different remediation strategies, and for identifying studies needed to support assessments.
- Development of appropriate site characterisation programme, accounting for the environmental effects of field work.
- Protocols for selecting appropriate remediation strategy (possibly targeting particularly troublesome contaminants).
- Cost-benefit analysis of proposed remediation measures, based on quantitative analysis produced by this structured approach.
- Analysis of effects of uncertainty in data describing system under investigation.
- Designation of suitable criteria for terminating clean-up process and for monitoring success.

assessment. There is reason to suspect that courts do not fully understand concepts of probability and uncertainty and that they will avoid looking closely at technical controversies if they can find an alternate basis for resolving disputes."

The methodologies of risk assessment and decision analysis could provide the framework for a more systematic approach to groundwater contamination. Such an approach is set out in Box 10.2.

For example, in the USA, the Resource Compensation and Recovery Act allows as a clean-up target a site-specific risk-based action level, which is an alternative to either background or EPA-specified levels. In the UK, quantitative risk analysis methods have only tended to be applied or researched for a limited number of groundwater management topics (eg contaminated land and toxicology). The aims of the recently formed *Forum for Contaminated Land* include: an "... attempt to develop a structured approach to risk assessment ...". The Centre for the Study of Financial Innovation (CSFI) has put together a working group to prepare a methodology for ascribing an environmental risk rating to companies, analogous to credit ratings, which would inform the market.

Needs

Ultimately, many decisions are driven by the power of the lobby and the media. Groundwater specialists and the public often have very different perceptions of risk. Huge sales of bottled water are evidence of this difference, with often diametrically opposed views! The various views are continually revisited in the media. Whether perceived risks should be taken into account in risk management is an issue in itself. Public awareness, fostered through targeted education, about absolute and relative risks is important in attaining rational risk-based management of water resources.

There is a broad need to investigate the applicability of quantitative risk assessment to a range of groundwater management issues. Such work will help to ensure that legislative and policy statements which relate to risk are pragmatic. More specific needs include: the need to evaluate risk analysis software, continued and expanded toxicological studies, and public education.

11. Key conclusions on groundwater issues and perspectives

Introduction

In this Chapter, key conclusions are distilled from the review of groundwater issues, institutional perspectives and priority research needs. While this discussion may not be comprehensive, it seeks to provide a relatively balanced and objective insight into key questions, some of which are complex and relatively intractable, some simple but generally unrecognised. While this approach to concluding a report that apparently focuses on the technical aspects of groundwater management may be unusual, it is fitting in a report that seeks to provide a broad overview of such a complex and poorly understood, but important strategic and environmental resource.

BOX 11.1 Possible Elements of Sustainable Groundwater Development

Possible management goal:

- To ensure that the benefits to different users provided by a groundwater / aquifer system will meet present objectives of society without compromising the ability of the system to meet future objectives

Possible objectives of society:

- Economic productivity and efficiency ('wealth creation')
- Equity
- Human health
- Environmental protection

(Equity, Human health and Environmental protection: 'quality of life')

Possible conflicts and trade-offs:

- Interests of present vs future generations
- Groundwater development for one use vs another
- Abstraction for supply vs environmental needs
- Groundwater protection vs unrestricted economic activity
- Lowest price water to consumers vs environmental protection and full cost pricing

Sustainability

The concept of sustainability is often employed in this Report with regard to groundwater management and development and in relation to the needs of society and the environment. This concept is open to wide interpretation, however; it is not clearly defined and can be used to justify a diverse range of actions (Box 11.1).

In general, the concept of sustainable water resources management incorporates ideas of costs and benefits to present and future generations. If activities which influence the groundwater system, such as pumping and pollution, can be managed in such a way that the overall welfare of society is increased without sacrificing the interests of future generations, then that method of management can be considered sustainable. Welfare might be derived from a broad array of water uses, ranging from domestic, agricultural and industrial to the maintenance of ecosystems. However, sustainable management does not mean that everything must remain the same, with the existing quality and quantity of water resources remaining intact.

Rather, it is the value to society of different water uses that are to be maintained or increased. These values might include economic productivity, human health, and environmental quality.

In addition, there is a scale question: welfare benefits to a small group could bring welfare benefits or disbenefits to society as a whole (eg as could be argued one way or another in the cases of maintaining agricultural communities or maintaining headwater streamflows for recreational fishing); similarly preventing environmental damage at the local scale may bring environmental benefits or disbenefits at a larger scale (eg as could be argued either way for inter-basin transfers). Clarity over the meaning of sustainability in groundwater management is obviously important and should be sought; there are trade-offs to be considered and economic questions to be asked.

Economic questions

In addition to understanding the science of the processes underpinning the groundwater issues, it is clear that a significant part of the solution to some of the groundwater issues will lie in answering questions of economics and the political economy. In the case of groundwater, little good conceptual work has been done, either in the UK or elsewhere, that applies new concepts of environmental and institutional economics to:

- Groundwater resources degradation (both in terms of quantity and quality) caused by anthropogenic activity. Degradation does not refer to *changes* in quantity or quality caused by anthropogenic activity, as these changes may be beneficial (lowered water levels enhancing recharge or reducing flood risk; scavenger pumping improving quality), but could be defined as *a reduction in the value (in constant terms) of stock as a consequence of changes in quantity or quality.*

- The consequent impacts of degraded *or* exploited but undegraded groundwater resources on society and the ecosystem. Impacts could be physical (eg subsidence, or reduced surface flows), financial/economic (eg increased costs of supply), or environmental (eg reduced biodiversity). Impacts may also be intergenerational (eg the loss of the physical aquifer fabric as a natural resource asset, or the loss of an ecological resource).

The economics of groundwater development are thus intricately linked with the viability of groundwater management strategies and the enforceability of pollution protection and abstraction policies, and trade-offs are apparent. For example, instruments of an abstraction policy (eg regulatory, such as licensing, or economic, such as pricing) will generally increase the costs faced by users, while bringing environmental benefits. What are these costs and benefits and what is the consumer 'willingness to pay'? Protection policies have significant impacts on agricultural practices and industrial processes, possibly increasing investment and operating costs and thus reducing profitability or increasing consumer prices. An important analytical question, needing inputs from environmental economic analysis, that would pose significant theoretical problems, is whether to protect upstream (ie in the catchment) or to treat downstream (ie at the borehole). Again there are several important and explicit trade-offs to be made. Since privatisation and the establishment of the current institutional framework, there has been divergence between the pricing signals of OFWAT, which represents customers and surrogate competition and holds prices down, and the NRA, which seeks to protect the water environment, tending to push prices up. A further important area for economic analysis is that of the costs of groundwater clean-up and the value of benefits, both to public supplies and to the environment.

Little explicit economic analysis of these issues has been undertaken. The risk of avoiding such an analysis is that policies will be developed to meet intuitively sound or politically expedient principles of environmental protection, while incentives for enforcement of those policies will be limited. The economic cases of agriculture and industry can be readily made and these industries represent the engine of the nation's economy. Thus the economic case for groundwater protection, both from pollution and over-exploitation, needs to be well presented. This case will require pricing of natural resource assets, including groundwater resources, uncontaminated aquifer storage reservoirs, and groundwater-fed streams and wetlands (and their associated habitats). Coupling economic analysis to scientific studies of groundwater flow and quality regimes would require rare interdisciplinary effort but could make a significant contribution to resolving the otherwise intractable questions of decision criteria for some of the more important issues. Promoting such studies is a key conclusion of this Report.

Broad perspectives

As would be expected, many different perspectives, discussed at some length in Chapter 5, emerged from the consultations regarding the groundwater issues and the concept of sustainable groundwater development. One overall emerging theme is the essentially ethical conflict over the 'condition' at which our environment should be preserved. Our environment has been 'engineered' for centuries, with (for example) meadows, woodlands, hedgerows and a 'built' environment that bear little resemblance to a 'pristine' landscape. Groundwater flowing into surface water plays its part in sustaining the environment that we know. Maintaining that status quo - or restoring it to what we perceive to be an earlier status quo - is clearly one, not unreasonable, goal. But we still choose to pick those historical conditions that we would prefer to avoid: high water levels below London's central business district; the return to waterlogged land in coalfield areas which have been arable farmland for over a century due to dewatering by mine pumping; flood risks in formerly flashy rivers. The questions of engineering perennial rather than ephemeral flows, or sustaining vulnerable wetlands are fraught with the dilemmas of sustainable development, discussed above. There is, of course, the option, increasingly adopted, of artificially sustaining important environmental assets, through compensation pumping, thus engineering both substantial groundwater resource development and environmental conservation. This, however, also raises ethical questions and potential conflicts, not least in public perceptions.

Public perceptions appear to be, to some extent, bipolar, with concern for rising costs of water on the one hand and increasing concern at damage to the water environment on the other. Perceptions of risk are possibly characterised, in part at least, by growing use of bottled water for drinking. There appears to be generally very little public understanding of groundwater flow and quality, and this is often compounded by poor representation in the media - often inferring 'underground rivers'. Enhanced public awareness of groundwater and its role in our daily lives and the landscape, and public participation in decision making on some of the more intractable ethical questions, could make a significant contribution to sustainable groundwater management.

Other perspectives have been discussed elsewhere in the Report, and key conclusions only are drawn here. Taking the public sector, within the water quantity and quality regulators there is overriding concern for the environment in the search for the sustainable development of groundwater, a complex resource which is recognised as a least-cost option for public supply. The precautionary principle is firmly applied, although this may mean very conservative judgements due to lack of knowledge and consequent uncertainty. The perceptions in some government departments may differ from this, due to their interests in other sectors of the economy. Overall, however, there is a clear commitment to sustainability, although, at least in terms of groundwater use, this remains undefined. Definition, at least in the form of guidelines, would be valuable, although this would not be as easy to conceive as with many other natural resource assets.

Perceptions of the water industry are driven by concern over the impacts of tight quantity, quality and price regulation on profits and thus on share prices. The uncertainties surrounding groundwater are reflected in major commercial risks, which cause great concern. The threat to sources - the primary asset - from revoked licences and unpredicted contaminants is a primary concern. While behaving in an environmentally responsible manner is clearly an industry goal, proactive action by the industry could provoke precautionary decisions by a regulator which have serious commercial implications. The industry would clearly like to see groundwater protection policies implemented as effectively as possible, as it will itself be a primary beneficiary. Reducing uncertainties, thus narrowing the gap between conservative decisions and well-informed decisions, is a major priority of the industry, and clearly is also important for the regulator due to the overall benefits to the economy.

Environmental organisations perceive excessive groundwater development to be the cause of significant negative environmental impacts, and wish to see reduced abstraction. Consumptive industries affected by revoked groundwater abstraction licences and by groundwater protection policies (especially agriculture) believe that the costs to the UK economy of restricting their activities can be much higher than the benefits. Again, there is a general concern that there are few incentives for environmentally sound behaviour by industry. If a contaminant spill were reported instantly, remedial action could be swift. This would give more chance of being effective before contaminant dispersal occurs into an aquifer. However, there are disincentives for reporting, due to 'polluter pays' liability, and with time it becomes more difficult to identify a culprit. In order to encourage the reporting of spills, an amnesty period or other incentive might be considered.

BOX 11.2 Maastricht Treaty: Title XVI Environment, Extracts from Article 130r

Objectives

- preserving, protecting and improving the quality of the environment;
- protecting human health;
- prudent and rational utilisation of natural resources;
- etc

Principles

- Community policy shall aim at a high level of protection taking into account the diversity of situations in the various regions of the Community.

It shall be based on the precautionary principle and the principles that:
- preventative action should be taken;
- environmental damage should be rectified at source;
- the polluter should pay.

New proposals must take account of:
- available scientific and technical data;
- the potential benefits and costs of action or lack of action.
  preserving, protecting and improving the quality of the environment;
- protecting human health;
- prudent and rational utilisation of natural resources.

These broad perspectives make it clear that all interested parties would benefit from greater understanding of the groundwater environment, and the greater precision that this would bring to groundwater management decisions.

Quality: the protection vs treatment question

The consultation process put in sharp relief the protect 'upstream' / treat 'downstream' debate. The aims of the NRA and other regulatory authorities are clear, and they mirror the statement of principles in Article 130r of the Maastricht Treaty (see Box 11.2). The NRA's new Policy and Practice for the Protection of Groundwater is evidence of these aims, and it represents a significant potential investment by the UK economy.

However, in practice the situation is affected by both the pollution legacy, which is widespread, long-term and not well defined and understood, and the difficulties of ensuring protection and identifying culprits, due to the complex groundwater environment. As a consequence of perceived risk, some water companies are investing, or considering investing, in comprehensive treatment facilities. Organisations representing the agricultural community have argued that this is the correct economic route to take.

The effect is that it is no longer a choice between protecting 'upstream', in accordance with national and European policy, or treating 'downstream', which could possibly be a rational economic step. Instead, both actions - protection and treatment - are being adopted. Both actions together raise the costs to the economy significantly (to the potential polluters as well as to the consumers). If increasing economic costs of protection do not result in decreasing costs of treatment, then there is a problem that needs to be resolved. Ultimately, an optimum path may be a combination of an appropriate level of protection 'upstream' and of treatment 'downstream'. A conclusion of this report is that detailed study of this subject should bring major benefits.

BOX 11.3 Aquifer Storage Recovery in the USA

In the United States the concept of artificial recharge of groundwater has recently been developed to include the use of non-potable or saline aquifers for storage of water. The injected water (generally treated to potable standards to avoid clogging problems) forms a lens of good-quality water within the saline water body for later recovery. This development greatly increases the potential for using artificial recharge, or Aquifer Storage Recovery (ASR). The main objective of using ASR is to manage water resources by use of aquifer storage as a strategic reservoir to meet variations in demand, almost irrespective of native groundwater quality, using almost no land area and having minimal environmental impact.

Operation of a typical ASR installation is designed to smooth out annual variability by recharging aquifers during periods of low demand and recovering the water during periods of high demand. When a non-potable or saline aquifer is used as the ASR reservoir, the saline water has to be flushed from the fractures and pore spaces, a process that requires several cycles for the scheme to become fully operational. With each cycle, the percentage of water of acceptable quality recovered progressively approaches the quailty of the recharge water.

The number of operational ASR schemes installed in the United States has increased dramatically in the last four years (from 10 to 20 with 40 more in development) as the technology and methodologies have become established and accepted. Schemes have been installed in a wide variety of hydrogeological environments and have recovery capacities varying from 2 to 385 Ml/d. The capital costs of several schemes that have been implemented in the United States range from £35,000 per Ml/d to £290,000 per Ml/d. These costs are not directly comparable with British costs but provide a useful indication of scale. Similarly, a comparison of costs for expansion of five schemes in the United States show ASR schemes to be between 5% to 43% of the cost of a scheme not using ASR.

Ref: Pyne, RDG. 1995. Groundwater recharge and wells: A guide to Aquifer Storage Recovery. Lewis Publishers.

Quantity: the storage, conjunctive use and compensation questions

The UK has relatively abundant water resources, but they are seasonally distributed and rapidly lost to the sea. Thus the problem is largely one of meeting peak demands during times of low rainfall and low river flows, through providing storage close to centres of demand. The groundwater quantity questions revolve around the effective management of groundwater storage to optimise water resources development while minimising environmental effects, particularly on sensitive river flows and wetlands. Some people consulted perceived groundwater pumping to be the cause of many problems and that greater investments in surface reservoirs to capture abundant river flows would be a solution, despite the considerable potential storage of UK aquifers. This general view of groundwater is relatively widespread. In part this represents a significant shift over the last three decades, as in the 1960s and 1970s use of groundwater storage was actively promoted, due to widespread opposition to new reservoirs.

Pioneering work in the 1960s and 1970s, led by the Water Resources Board (WRB), demonstrated the benefits that could be derived from conjunctive use of surface water and groundwater, which exploits groundwater storage for river regulation to meet peak demand downstream and also for providing compensation flows for environmental purposes. The WRB work also revealed many problems, particularly in the Chalk. The Chalk typically has a low storage coefficient and a high transmissivity, causing pumping effects to be propagated rapidly, which may then affect stream flows. Conjunctive use locations in the Chalk therefore need to be selected where storage coefficients are unusually high (as in the Candover Scheme) or where boreholes can be distant from the river, although this increases conveyance costs and reduces benefit. Triassic sandstones have a lower transmissivity and higher storage coefficient than the Chalk. This has enabled the successful Shropshire Groundwater Scheme. Development of conjunctive use schemes are now a demonstrated and accepted water resources management strategy. Nevertheless, existing schemes are little used, partly because the new institutional framework for water means that the water industry is primarily interested in river regulation for ensuring downstream supplies (eg for pumped storage reservoirs) and the NRA's interest is primarily in river regulation to satisfy environmental objectives. Conjunctive use means taking both into account, and institutional and financial mechanisms need to be established on a case by case basis, as they have been in the Shropshire Groundwater Scheme, where the NRA is the 'operator' for both environmental purposes and for the water companies. In addition, due to relatively high operating costs, schemes are regarded primarily as insurance policies (with low capital cost), only to be used when needed.

A further strategy which has been investigated in the UK for several decades is that of augmentation of groundwater storage through artificial recharge. The most significant scheme in operation is the Lee Valley/Enfield-Haringey Artificial Recharge Scheme in North London, where surplus treated mains water is injected into the dewatered Chalk aquifer and the Lower London Tertiary sands, which are overlain by the London Clay. The Scheme is designed to provide strategic drought storage and demonstrates that imaginative management of groundwater, including artificially replenishing the reservoir in periods when supply exceeds demand, can provide a sustainable resource with minimum environmental impacts. However, in recent strategic planning, artificial recharge of groundwater has been excluded as an option for development, largely on the grounds of a perceived lack of suitable geological structures. Nevertheless, it is recognised that further studies are needed to identify additional favourable sites.

In the 1960s the Water Resources Board initiated an extensive series of field investigations of the feasibility of artificially recharging the principal British aquifers by means of basins and wells, and no practical problems were encountered. In addition, some artificial recharge in Britain has focused on replenishing freshwater aquifers with tertiary treated water or the disposal of wastewater through seepage lagoons, channels and drains. Recharge in the latter case is incidental, as the key objective is wastewater disposal.

In the light of the recent experience gained in the United States with Aquifer Storage Recovery (ASR), studies should be expanded to include non-potable aquifers as potential groundwater reservoirs (see Box 11.3). Attention needs to be focused on areas with the greatest potential, not only from the hydrogeological point of view but also where an ASR scheme could meet a genuine demand. Areas likely to benefit most from this type of scheme, assuming appropriate geological structures exist, would include coastal holiday areas which have difficulty in meeting peak summer demands.

ASR deserves careful study, as a possible solution to many of the quantity-related groundwater issues as well as a potential strategy for long-term water resources management in the UK, possibly limiting the need for new surface storage and inter-basin transfers in areas where ASR is viable, particularly in currently unrecognised, permeable, confined aquifers containing non-potable groundwater. It is possible that this could substantially increase storage capacity in key areas of the UK at low cost, and with minimal environmental impact.

Investing in groundwater research

This Report identifies a number of areas for groundwater research, including research on operational, applied and underpinning process questions, as well as on economic and policy questions. If all this work were to be undertaken, the overall cost would be very high, although benefits could be commensurate. Nevertheless, resource constraints will clearly severely limit any future research programme and priorities must be set. The Report seeks to do that and a summary of recommendations is given in Chapter 12.

However, the question of scale of investment in groundwater R&D needs to be addressed. Relevant facts include:

- although figures are not available, due to the absence of any research coordination, the total spend on research that specifically targets potable groundwater as its primary objective in the UK by all parties could be less than £1.5 million per year and is unlikely to exceed £3 million; the public sector spend is less than £1 million; all for a resource that:
  - provides supplies to about 20 million people,
  - provides all of our bottled water,
  - is a crucial strategic store of water,
  - maintains river flows and wetlands;
- groundwater sales in England and Wales for public water supply (after treatment and reticulation) are about 2,000 million cubic metres per year, with an annual sales value of, say, £1.2 billion; groundwater abstraction for industry, agriculture and fish farming yields a further 500 million cubic metres per year;
- private, unregulated supplies (almost all groundwater) are estimated to withdraw an estimated 50 million cubic metres a year to supply about 500,000 people, at a notional value of £30 million;
- bottled water sales (all groundwater) are about 545 million litres per year, with a sales value of about £240 million;
- industry expenditures on treatment of contaminated groundwater are very high; the written answers by the Secretary of State for the Environment (*Hansard*, 30/11/94) stated that: "Water industry capital expenditure on the drinking water compliance programme during the period 1990-91 to 1993-94 was around £2.5 billion at 1993-94 prices"; and ".. I understand that capital expenditure by water companies in England and Wales on new treatment to remove pesticides from water put into supply was £122 million in 1992-93 and that in 1993-94 and 1994-95 companies were planning to spend £170 million and £207 million respectively..." A high proportion of expenditures on pesticide and nitrate treatment will be on groundwaters. These costs do not include recurrent spends;
- although not directly relevant, the equivalent spend on hydrogeological research related to radioactive waste disposal in the near-impermeable Borrowdale Volcanics Group in a corner of north-west England is more than an order of magnitude higher per year than the spend on research into the hydrogeology of the remaining UK aquifers.

It would appear that the research spend bears little rational relationship with the social, environmental, and economic importance of groundwater or the cumulative financial spends on licensing and treatment and the associated total price paid by consumers. A conclusion is that a coordinated research programme, drawing together many of the interested parties and addressing the priority issues set out in this Report, could possibly justify funding at a level significantly higher than the level of current funding. Selecting a wholly arbitrary figure, if the research spend was 1% of groundwater sales, it would be £15 million per year, about seven times the estimated current spend. In setting a rational target for the scale of UK Groundwater R&D, it would be useful to survey the equivalent spends of other European countries. In drawing these conclusions, it is recognised that other research, such as MAFF's work on pesticides and nitrate, makes some contribution to groundwater knowledge.

12. Recommendations: A National Groundwater R&D Agenda

Summary

Chapters 12 and 13 comprise recommendations drawn from different parts of the Report. The recommendations fall within two broad themes, both emerging directly from the process and findings of the Study.

Theme 1. A National Groundwater R&D Agenda. *A national groundwater R&D agenda is recommended, focusing in the medium term on the priority issues identified in the Study. A shorter term R&D programme is proposed in detail. The national programme will build upon, and not replace, current research and the work of individual research customers, and will promote value for money through cooperation and information sharing.*

Theme 2. The UK Groundwater Forum. *It is recommended that the dialogue between the stakeholders, initiated by the Study, should be sustained and extended, to promote: discussion of the issues facing UK groundwater resources; cooperative action among the different stakeholders in addressing those issues; and wider information dissemination, to seek public understanding of the importance of groundwater as a resource and to form a consensus on policy directions.*

National Groundwater R&D Agenda

As a result of this Study it is clear that a priority national groundwater R&D agenda exists which needs - and justifies - a greater level of investment than is currently made. Cooperative structures, through the UK Groundwater Forum, are recommended above, which will ensure that such an agenda is developed and implemented in a cost-effective way. Even if no net additional funding becomes available, we can, as a result of this Study, ensure that current research investments are more effectively used and provide benefits across a broader spectrum.

A National Groundwater R&D Agenda will have the following broad elements:

- A primary objective will be to reduce uncertainty and risk. Through the use of targeted monitoring, other data collection and R&D, understanding of the groundwater environment will be improved and uncertainty reduced, thereby bringing precision to groundwater management and reducing risk. This will close the often wide gap between conservative precautionary decisions and correct ones, reducing costs to industry and increasing economic benefits to society as a whole. The development of tools for handling uncertainty and procedures for quantitative risk assessment will be required (Chapter 10).

- A further objective will be to establish coupled economic and scientific (hydrogeological and ecological) studies in the interdisciplinary analysis of environmental impacts and economic costs and benefits. The main goals are to clarify the concept of sustainable groundwater development and to analyse groundwater management strategies, particularly those for: groundwater protection from pollution; abstraction licensing and the maintenance of flows and wetlands; and remediation/ restoration (Chapter 11). In addition, acceptable cost-benefit methodology will be established for use throughout the industry.

- The National Groundwater R&D Agenda will focus primarily on the 14 priority issues identified by this Study (Box 6.1), with the main R&D requirements set out in Tables 8.1 to 8.14. There may be other important areas of R&D related to issues not rated as priority in this Study, which should therefore not be ignored. An appropriate programme of operational research (Boxes 8.2 and 8.3), applied research, hydrogeological processes research (Box 8.4) and tool development/ refinement (Chapter 9) needs to be further developed and adopted. In addition, underpinning work on survey and mapping of groundwater resources needs to be sustained and in places extended, and some current strategic research continued.

- National groundwater research and demonstration sites and catchments will be sought, wherever possible building, in an 'opportunistic' way, on existing and planned operations and site investigations which are funded by the regulators, water industry, other industry, research councils etc. The objective will be to seek maximum R&D returns at minimum cost and allow a wide range of groundwater issues to be addressed by different researchers and research customers (public and private). Additional scientific and economic advantage would be gained if several sites could be established within a single catchment. Priority sites could include: 'test borehole' sites on major aquifer types; 'stream/aquifer interaction' and 'wetland/aquifer interaction' sites; lysimeter sites; and clean-up/contaminated sites. If specific national groundwater research sites need to be established/sustained, infrastructure and recurrent costs could be drawn from 'rental' charges; in some circumstances, it may be possible to obtain infrastructure investment costs directly from a research customer.

- Effective research management will be a critical element of a successful National Groundwater R&D Agenda. During the Study, many comments were received regarding the management of research.

Recurring themes included:

- the need to seek best value for money, which may be dervied from substantive, collaborative R&D programmes; in some cases, this may preclude the use of competitive tendering;
- the need to nurture customer/ contractor relationships, which are crucial to effective R&D, particularly for long-term strategic work, giving some continuity and stability while maintaining efficiency; and
- the need to ensure training and appropriate incentives/rewards in customer organisations for project leaders, to strengthen their capacity for research management.

- A priority R&D agenda is recommended. Within the overall framework of the 14 priority issues, specific R&D topics that deserve immediate attention within a priority R&D agenda are given in Box 12.1. R&D topics are grouped within four topic areas, 'Generic and Cross-Cutting', 'Agriculture', 'Industry', and 'Catchment Management'. The identified topics represent work that is either not being undertaken or is significantly under-funded and:
  - is specifically identified within a priority issue listed in this Report;
  - is specifically identified by several issues; and
  - is needed to underpin a significant number of the specific R&D needs ('Generic and Cross-Cutting').

Priority projects in each of the four areas were chosen on the basis of one or more of the following;

- topic is important and hardly addressed; in many cases a review or a scoping study is proposed, to identify needs and actions;
- significant progress is likely within a moderate time relative to the complexity and importance of the problem (ie good 'value for money');
- work that is of importance and will benefit from an early start;
- no obvious technical, scientific or institutional bar to progress.

Finally, ongoing R&D is NOT included, although this may be under-funded and essential (such as groundwater survey and mapping). Such work must continue to be funded. The priority R&D agenda listed is supplementary to this ongoing work.

BOX 12.1. GROUNDWATER R&D AGENDA: short to medium term priority projects (including scoping studies) building on current/planned work. The projects highlighted in bold within each of the four main topic areas are considered to be top priorities.

Topic Area A. GENERIC and CROSS-CUTTING

Project:	**1. Risk assessment methodologies for groundwater protection and management. (Scoping study only.)**	**2. Coupled hydrogeological, ecological and economic analysis of sustainable groundwater development. (Scoping study only.)**	**3. Groundwater data collation in Scotland.**	4. Hydrogeochemical database for UK aquifers. (Scoping study only.)	5. Development of laboratory-validated reactive transport models of the saturated zone.
Justification:	**An improved rationale for groundwater protection and management is needed to refine the precautionary element of management decisions in the presence of uncertainty.**	**Need to bring together hydrogeology, ecology and environmental economics to develop rigorous sustainable management strategies, particularly for groundwater pollution control and abstraction licensing.**	**Groundwater data in Scotland are sparse and dispersed. Their collation and databasing is a prerequisite for groundwater management and for a groundwater R&D programme.**	A database of mineralogical and chemical properties of aquifers is required for pollutant transport modelling.	Groundwater protection and management requires functional reactive transport models which are validated.
Description:	**Scoping study will review the use and scope of suitable methodologies.**	**A multi-party scoping study will review conceptual approaches and models, and will identify case studies.**	**Study will collate Scottish groundwater quantity and quality data and establish database.**	Scoping study will review data requirements for pollutant transport models and data availability for an aquifer chemical database.	Study will develop reactive transport models and undertake extensive laboratory validation.
Annual Cost (project duration):	**£30K (1 yr)**	**£40K (1 yr)**	**£50K (2 yrs)**	£30K (1 yr)	£90K (3 yrs)
European Interest:	**	***			***
Beneficiaries:	**CEGIR**	**CEGINR**	**CGR**	INR	CNR

Key: Top Priority Projects in each Topic Area are denoted by **bold** text. Potential European Interest is based on the likely number of partners, ie EU countries with similar interests. The key is as follows: * at least one partner, ** two to five partners, and *** more than five partners. A number of beneficiaries of specific projects are identified. The key to the beneficiaries is as follows: C, water utilities; E, environmental NGOs; G, government; I, industry (users); N, research councils; and R, regulators.

BOX 12.1 (continued). GROUNDWATER R&D AGENDA: short to medium term priority projects (including scoping studies) building on current/planned work. The projects highlighted in bold within each of the four main topic areas are considered to be top priorities.

Topic Area A (continued). GENERIC and CROSS-CUTTING

Project:	6. Three-dimensional saturated zone flow and aquifer properties' heterogeneity. (Scoping study only.)	7. The effects of fracturing on the hydrogeology of the Permo-Triassic sandstones.	8. Stochastic model for solute movement through the unsaturated zone of fractured aquifers.	9. Pollution and flux measurement sensors.	10. Decision support systems (DSS) for groundwater management (Scoping study only.)
Justification:	Three-dimensional flow, including long deep pathways from interfluves to sources and flow in the vicinity of boreholes, is poorly understood but essential for predicting long-term trends in water quality (eg future nitrate concentrations).	Groundwater in sandstone aquifers is poorly understood through a lack of knowledge of the presence, extent and connectivity of fracture systems. Pumping tests tend to give ambiguous results and more sophisticated approaches are required.	Need to be able to predict the rate of movement of nitrate, pesticides and other pollutants through the unsaturated zone so as to be able to provide a reliable pollutant source term for saturated zone models.	Too much reliance is often placed on the modelling of water and solute fluxes. Need direct methods for continuous monitoring.	R&D results need to be integrated in a form suitable for groundwater management. DSS provide potentially powerful tools that should facilitate the application of R&D results in an operational environment.
Description:	Scoping study of the effects of 3-D flow and dilution on long-term water quality. Evaluate options and costs for obtaining adequate 3-D aquifer properties.	Study will include the combined use of field characterisation techniques, pumping tests, tracer tests, and geophysics.	Study will develop field-scale models and undertake extensive validation using tracer tests.	Study will define requirements, and identify/ adapt/develop and test appropriate sensors, or sampling devices.	Scoping study will review needs and capabilities of DSS. Identify existing DSS availability and define future applications, and development needs.
Annual Cost (project duration):	£40K (1 yr)	£100K (3 yrs)	£120K (3 yrs)	£50K (2 yrs)	£30K (1 yr)
European Interest:	**		**	**	**
Beneficiaries:	CGNR	CNR	CNR	CGINR	CGR

Key: Top Priority Projects in each Topic Area are denoted by **bold** text. Potential European Interest is based on the likely number of partners, ie EU countries with similar interests. The key is as follows: * at least one partner, ** two to five partners, and *** more than five partners. A number of beneficiaries of specific projects are identified. The key to the beneficiaries is as follows: C, water utilities; E, environmental NGOs; G, government; I, industry (users); N, research councils; and R, regulators.

BOX 12.1 (continued). GROUNDWATER R&D AGENDA: short to medium term priority projects (including scoping studies) building on current/planned work. The projects highlighted in bold within each of the four main topic areas are considered to be top priorities.

Topic Area B. AGRICULTURE

Priority Issues: Nitrate, Pesticides

Project:	**11. Pesticide baseline survey. (Scoping study only.)**	12. Nitrate catchment models (building on Projects 6 and 8 above).	13. The rates of pesticide degradation in aquifers. (Scoping study only.)		
Justification:	**There are very few data on the scale and extent of the pesticide legacy in the unsaturated zone and shallow saturated zone; the data are essential for predicting pesticide concentrations at groundwater sources.**	Cost-effective management of nitrate concentrations at sources requires improved catchment models which would also guide aquifer protection strategy.	The planning of the treatment of pesticide-contaminated groundwater suffers from a paucity of data on the rates of pesticide degradation in UK aquifers. Some evidence suggests very slow rates of degradation. This has significant management implications.		
Description:	**Scoping study will include review of pesticide usage, compounds and application environments, pesticide transformation products, and sampling techniques for the unsaturated zone.**	Study will test a range of models of varying degrees of sophistication using nitrate leaching histories, effective rainfall data and groundwater nitrate concentration data.	Scoping study will review methods for determining the rates of pesticide degradation and metabolite formation under *in-situ* conditions.		
Annual Cost (project duration):	**£30K (1 yr)**	£50K (3 yrs)	£30K (1 yr)		
European Interest:	**	***	**		
Beneficiaries:	**CEGNIR**	CGINR	CIR		

Key: Top Priority Projects in each Topic Area are denoted by **bold** text. Potential European Interest is based on the likely number of partners, ie EU countries with similar interests. The key is as follows: * at least one partner, ** two to five partners, and *** more than five partners. A number of beneficiaries of specific projects are identified. The key to the beneficiaries is as follows: C, water utilities; E, environmental NGOs; G, government; I, industry (users); N, research councils; and R, regulators.

BOX 12.1 (continued). GROUNDWATER R&D AGENDA: short to medium term priority projects (including scoping studies) building on current/planned work. The projects highlighted in bold within each of the four main topic areas are considered to be top priorities.

Topic Area C. INDUSTRY

Priority Issues: Acid mine drainage, Contaminated land, Landfill, NAPLs, Remediation

Project:	**14. Effective groundwater clean-up.**	15. Transport properties of common groundwater contaminants emanating from contaminated land. (Scoping study only.)	16. Coupled models of flow and chemistry in abandoned deep-mined strata.	17. Fundamental processes of DNAPL migration in UK aquifers.	
Justification:	**Effective procedures for clean-up require improved modelling, sampling methodologies and risk assessment, all of which would greatly benefit from detailed monitoring of a range of field sites.**	An understanding of the transport properties of common groundwater contaminants would inform the investigation of specific contaminated land sites in terms of pollution risks to groundwater.	Needed to predict the extent and longevity of acid mine drainage and its impact on surface and groundwater quality. Existing groundwater flow models are unsuitable for mine environments.	The rate at which DNAPL-contaminated aquifers are cleansed by uncontaminated water is poorly understood, both under natural flow conditions and during clean-up.	
Description:	**Study will monitor in detail and analyse the efficacy of clean-up at a number of ongoing clean-up operations as opportunities arise.**	Scoping study will review the transport properties of common contaminants and cocktails of contaminants in UK aquifers.	Study will develop and apply practical models for the prediction of the quantity, quality, and impact of drainage waters from abandoned mines.	Theoretical and laboratory studies will investigate DNAPL transport, including the extent and the role of residual saturation.	
Annual Cost (project duration):	**Above £100K (5 yrs)**	£25K (1 yr)	£70K (3 yrs)	£70K (3 yrs)	
European Interest:	***	***	**	*	
Beneficiaries:	**CGIR**	CEIR	CIR	CIR	

Key: Top Priority Projects in each Topic Area are denoted by **bold** text. Potential European Interest is based on the likely number of partners, ie EU countries with similar interests. The key is as follows: * at least one partner, ** two to five partners, and *** more than five partners. A number of beneficiaries of specific projects are identified. The key to the beneficiaries is as follows: C, water utilities; E, environmental NGOs; G, government; I, industry (users); N, research councils; and R, regulators.

BOX 12.1 (continued). GROUNDWATER R&D AGENDA: short to medium term priority projects (including scoping studies) building on current/planned work. The projects highlighted in bold within each of the four main topic areas are considered to be top priorities.

Topic Area D. CATCHMENT MANAGEMENT

Priority Issues: Afforestation, Land use change, Low flows, Resource protection

Project:	**18. Strategic monitoring of wetlands.**	**19. Surface water-groundwater interaction: the understanding of valley bottom hydrogeology.**	**20. Source protection zone models (particularly for fractured aquifers).**	21. Unsaturated zone storage. (Scoping study only.)	22. Deep groundwater storage - Aquifer Storage and Recovery, ASR. (Scoping study only.)
Justification:	**Rational management of wetlands requires an adequate scientific understanding of their hydrology and their relationship with ecology. Only a few of the many UK wetlands are currently monitored.**	**Increased understanding of valley bottom hydrogeological controls will help ensure effective environmental protection and cost effective groundwater resources.**	**Groundwater protection zone delineation is currently based on simplified assumptions. The resulting zone can be very large, particularly for fractured aquifers, and highly sensitive to hydrogeological uncertainties.**	The vulnerability of the major aquifers to drought may be significantly overestimated if slow movement through the often thick unsaturated zone is ignored. The problem can be exacerbated by climatic fluctuations.	Deep aquifers, which are not presently used because of poor quality water, might be used for cost-effective cyclic storage in places where seasonal water demand fluctuates significantly, eg near coastal towns.
Description:	**Study will design and implement a monitoring programme covering a wide range of UK wetland sites.**	**Detailed hydrogeological studies of selected catchments including monitoring based on data from dense monitoring networks.**	**Study based on risk assessment and stochastic models of flow and transport in both intergranular and fracture flow systems.**	Scoping study will review the significance of delayed recharge under various climatic scenarios, primarily concentrating on the Chalk aquifer.	Scoping study will identify the coincidence of aquifer storage potential and peak demands, to include economic, technological and ecological assessments.
Annual Cost (project duration):	**£75K (10 yrs)**	**£150K (5 yrs)**	**£50K (3 yrs)**	£30K (1 yr)	£50K (1 yr)
European Interest:	*	**	*	*	***
Beneficiaries:	**ENR**	**CNR**	**CGIR**	CGNR	CGR

Key: Top Priority Projects in each Topic Area are denoted by **bold** text. Potential European Interest is based on the likely number of partners, ie EU countries with similar interests. The key is as follows: * at least one partner, ** two to five partners, and *** more than five partners. A number of beneficiaries of specific projects are identified. The key to the beneficiaries is as follows: C, water utilities; E, environmental NGOs; G, government; I, industry (users); N, research councils; and R, regulators.

BOX 12.1 (continued). GROUNDWATER R&D AGENDA: short to medium term priority projects (including scoping studies) building on current/planned work. The projects highlighted in bold within each of the four main topic areas are considered to be top priorities.

Topic Area D (continued). CATCHMENT MANAGEMENT Priority Issues (continued): Source protection, Sustainable yield, Wetlands

Project:	23. Review of the pollution risks to groundwater sources in hard rock areas.	24. Review of the operation of groundwater development schemes, and development of sustainable land-use policies.	25. Regional groundwater models.	26. The impact of afforestation on water resources availability and its role in management. (Scoping study only)	
Justification:	Pollution risk assessment is a prerequisite for developing appropriate protection criteria for sources in vulnerable, minor, fracture-flow, aquifers. It is presently poorly understood.	More effective operation of groundwater schemes is needed, taking full account of environmental limitations (wetlands, baseflow needs) on yield and use.	Need to develop methods for combining small-scale models into improved regional models in a self-consistent way.	Afforestation can impact the quality and availability of both groundwater and surface water resources and enhance flood risk. Data for lowland broad-leaved woodlands is limited.	
Description:	Study will assess the impact of land-use and pollution (from agricultural point sources) on groundwater quality in Scotland, N Ireland, Wales and western England.	Study will review past performance of schemes and impacts of environmental constraints and assess strategies for optimising sustainable yields in accordance with the precautionary principle.	Study will review the approaches to consistent groundwater modelling at various scales, and develop a regional model for a selected area with interfaces to existing local models.	Scoping study will review impacts of broad-leaved woodlands in lowland areas on groundwater resources and quality and their interactions with surface water resources.	
Annual Cost (project duration):	£30K (1 yr)	£40K (1 yr)	£30K (3 yrs)	£30K (1 yr)	
European Interest:	*			*	
Beneficiaries:	CIR	CR	CNR	EGINR	

Key: Top Priority Projects in each Topic Area are denoted by **bold** text. Potential European Interest is based on the likely number of partners, ie EU countries with similar interests. The key is as follows: * at least one partner, ** two to five partners, and *** more than five partners. A number of beneficiaries of specific projects are identified. The key to the beneficiaries is as follows: C, water utilities; E, environmental NGOs; G, government; I, industry (users); N, research councils; and R, regulators.

13. Recommendations: The UK Groundwater Forum

This Report seeks to identify issues and research needs - ie where we need to get to. It is not the purpose of the Report to describe in detail how R&D should be managed by the customer and researcher at the project level - ie how we get there. This is, however, a topic that has arisen often during consultations and meetings, due to the extraordinary complexity of groundwater systems and the consequent importance of R&D. The lack of a coherent and coordinated R&D programme means that there is a risk of duplication due to lack of coordination between individual customer programmes. The interest in, and success of, the different consultation meetings held under this Study indicate the potential benefits of maintaining the *UK Groundwater Forum*, as a loose grouping of stakeholders meeting from time to time, to encourage sharing of research ideas and research resources, and to discuss and evaluate the issues and the products of reseach.

A primary justification for recommending maintaining the UK Groundwater Forum is the widespread support given by the consultees in the Study for promoting instruments of partnership, particularly between the regulators and the private sector, due to the many opportunities for learning which arise from operational activities and site investigations. Currently these opportunities are lost due to concerns over confidentiality and liability, as well as the lack of a forum for informal communication and exchange.

It is recommended that the *overall objective of the UK Groundwater Forum* would be:

to promote dialogue, consultation and partnership beween all public and private parties with an interest in groundwater resources, with primary emphasis on the sharing of research ideas, resources and products, and secondary emphasis on the discussion of questions of data, policy and standards, in order that groundwater issues are identified and resolved in the most cost-effective way, through cooperative efforts, and the findings are widely disseminated.

The *specific objectives of the UK Groundwater Forum* would include:

- to act as a vehicle for consultation between all public and private parties with an interest in groundwater, including data, research, policy initiatives and standards, in order that information is shared, opinions sought and, where possible, consensus achieved;

- to maintain a shared, user-led *National Groundwater R&D Agenda*, responding to user concerns and needs; to include an appropriate balance of underpinning strategic research, applied research and operational research;

- to promote public/private partnerships in R&D consortia addressing groundwater issues of national importance, thus minimising duplication of effort and maximising returns on research investments; instruments/incentives may need to be developed by the regulators to encourage transparency by and cooperation with private parties with commercial interests (eg some confidentiality by the regulator and public service charter by the industry) or those who are potentially liable (eg some level of amnesty by the regulator where historic site problems exist);

- to promote collaboration among research organisations (public and private), building on skills, sharing resources and equipment and encouraging information exchange;

- to disseminate research details and results widely among the researcher and user communities, by:
  - establishing a comprehensive national groundwater research database, incorporating all relevant and available research data and findings, for general access;
  - establishing a 'know-how' register of key players, identifying where to go for advice and promoting cooperation/avoiding duplication; and
  - promoting publication of research results and other information of interest, via printed and electronic media;

- to promote public information and awareness, due to widespread misconceptions and to the critical importance of groundwater to the welfare of our society and its environment, and thus build widespread consensus on the main issues and their solutions, through:
  - organising carefully targeted public awareness programmes;
  - building awareness among policymakers;

- to promote a unified approach to Europe in order to:
  - influence the research agenda;
  - ensure strong UK research programmes through synergy with European partners;
  - seek sources of matching funds for research that fits UK needs; and
  - promote UK skills and R&D findings in Europe.

It is recommended that the *UK Groundwater Forum be organised* as follows:

- The UK Groundwater Forum will be an ad-hoc and voluntary grouping of stakeholders, whose membership will include all who are prepared to contribute to achieving the above overall objective and who participate in any consultation exercise established to achieve the above specific objectives. Thus all consultees for the Study to date are members of the Forum, and all Study meetings have been Forum meetings.

- Initially, the Forum will have as a core group the Steering Committee established for this Study, representing NRA, WSA/WCA, NERC and FWR, whose function will be to promote the activities of the Forum. This core group may be reconstituted following a decision at a larger Forum meeting.

- The Chairman of the Forum will be elected at a larger Forum meeting, and will also chair the Steering Committee.

- The Forum will be served by a Secretariat of a single groundwater specialist, with access to secretarial support, who will prepare and follow-up meetings, maintain the research database, disseminate information (through printed and electronic media), and undertake other Secretariat and executive functions as required; this function is the only one requiring specific and non-discretionary funding, which the Steering Committee should seek to raise.

- Within the framework of the Forum, ad-hoc groups may be formed to promote specific activities, such as research coordination in a particular area (eg to cover the research areas proposed in Box 12.1); such groups will be optional and have a duration, structure, constitution and terms of reference appropriate to the task.

BOX 13.1 Recommendations for a UK Groundwater Forum

Overall objective

To promote dialogue , consultation and partnership between all public and private parties with an interest in groundwater resources with primary emphasis on the sharing of research ideas, resources and products, and secondary emphasis on the discussion of questions of data, policy and standards, in order that groundwater issues are identified and resolved in the most cost-effective way, through cooperative efforts, and the findings are widely disseminated.

Specific objectives

- to act as a vehicle for dialogue and consultation;
- to maintain a shared user-led National Groundwater R&D Agenda;
- to promote public/private partnerships in R&D consortia;
- to promote collaboration between research organisations;
- to disseminate research widely amongst researcher and user communities;
- to promote public information and awareness; and
- to promote a unified approach to Europe.

List of Participants and Consultees

Name	Organisation
Adams, J	University of Strathclyde
Agg, A R	Foundation for Water Research
Alexander, G	DoE (NI)
Allcock, R	Tay River Purification Board
Anderson, J	Tay River Purification Board
Anderson, J	Water Services Association
Armstrong, I	MAFF
Armstrong, R B	Southern Water Service
Armstrong, I	National Rivers Authority
Arnott, R	Scottish Office (Environment Dept)
Bailey, R A	Institute of Water and Environmental Management
Baker, M J	East Sussex County Council
Ball, D	BGS (Edinburgh)
Barker, J A	BGS
Bell, M	ICI
Bell, P	Hampshire County Council
Bennett, J R P	Hydro. & Env. Services
Bennett, A	Clyde River Purification Board
Best, G	Clyde River Purification Board
Beynon, R	WS Atkins - NI
Blackmore, J	WRC
Bliss, D	Leicestershire County Council
Bloomfield, J	British Geological Survey
Bone, R	Strathclyde Water
Borne, R	Strathclyde Water Services
Bradley, A	Confederation of British Industries
Britton, A	Strathclyde Water Services
Brown, D	SOAFD
Brown, R	Highland River Purification Board
Brown, D E	Chemical Industries Association Ltd
Burgess, D	Anglian Water Services
Burgess, W G	University College, London
Burgin, R	Cambridge Water Co.
Burns, J	Solway River Purification Board
Burrows, R	University of Liverpool
Butler, A P	Imperial College
Carter, P	BABTIE
Clark, L	WRC plc
Clough, H	Aspinwall
Connorton, B	Water Services Association
Cook, M	Anglian Water Services
Cook, H	Wye College
Crick, M J	University of Hertfordshire
Cruikshank, I	Solway River Purification Board
Curran, J C	Clyde River Purification Board
Currie, J C	Tweed River Purification Board
Curry, G B	University of Glasgow
Darbyshire, W	Lancashire County Council
Davies, A	Dwr Cymru Welsh Water
Debney, A G P	IH
Dent, C	AEA Technology
Dixon, J N	Surrey County Council
Duckworth, G	W/Mid Hazardous Waste Unit
Durning, B	Joint Countryside Advisory Service
Eastwood, J C	Wessex Water
Edge, J C	Anglian Water Services
Edmunds, C	The Council of Welsh Districts
Edwards, A C	Macaulay Institute
Elliott, J	Essex and Suffolk Water
Eriksen, H B	Solway River Purification Board
Evans, B	Borders Regional Council
Feast, N	School of Environmental Science
Flude, J	Water Companies Association
Forster, A	Geological Society
Foster, S S D	British Geological Survey
Fox, I A	Tweed River Purification Board
Fretwell, M	Leics WRA
Garraway, L	Wye College
Gellatley, M H	London Underground Limited
Gill, H L	Northumbrian Water Ltd
Gillies, W	Tay River Purification Board
Gledhill, L	Ove Arup
Gloak, B	Tay River Purification Board
Goody, N P	NE River Purification Board
Gordon, M J	Mike Gordon Consultancy
Gray, R	WS Atkins Environment
Grey, D R C	British Geological Survey
Gronow, J	DoE
Grout, M	NRA Anglian Region
Gunstone, J	SOED
Hagan, T	DoE (NI)
Haig, A	Clyde River Purification Board
Hall, K B	Hartlepool Water Co.
Hancock, C G	Somerset Wildlife Trust
Hardwick, D	Fertiliser Manufac. Ass.
Harris, R C	NRA - ST Region
Harrison, J G	Delft Geotechnics UK Ltd
Harryman, M	DOE/WD
Harvey, H J	The National Trust
Heath, A	National Power PLC
Herbert, A	Univ. of Birmingham
Hewitt, J M	County Waste Management
Hillier, S	MLURI
Hinchcliffe, P	DOE/UTD
Hiscock, K	UEA
Hodge, P G	Bristol Water plc
Holding, D A	Marks & Spencer plc
Hurry, A	BABTIE
Inglis, T	Highland River Purification Board
Jackson, N	DOE/CLL
Jarrett, M	South East Water
Johnson, R	IH (Stirling)
Jones, A	Welsh Office (Environment Dept)
Kalin, R	University of Belfast
Keith, L B	SOAFD
Kelcey, J G	JGK Environmental Consultancy
Kinniburgh, D G	BGS
Kinross, J H	Napier Univ, Edinburgh
Kirk, S	SWW
Leatherland, T M	Forth River Purification Board
Lee, S	Leicestershire County Council
Lees, P	Nottinghamshire County Council
Leslie, A E	Orkney Island Council
Lincoln, B	SOEnD
Ling, Pay Reg	Dumfries/Galloway Council
Lloyd, J W	University of Birmingham
Long, H	Council for Protection of Rural England
Lyness, D	Dept of the Environment (Northern Ireland)
Lythgo, M	Notts County Council
Macdonald, I	Department of the Environment
MacFarlane, D	SOEnD
Mackay, D W	NE River Purification Board
Mackay, D L	Rural Water Station Action Group
Marau, R	Wiltshire County Council
Margetts, L	Mid-Kent Water
Marshall, J	Cotswold Springwater
Matthews, P	Scottish Environ. Forum
McArdle, D	Whelan
McDonald, M	DG Env. Ltd
McEldowney, S	University of Westminster
McGill, C	United Distillers
McIntosh, E	DOE/WD
McvLeod, S	AEA Technology
Mellanby, J F	Grampian Regional Council
Misstear, B	Mott MacDonald Group
Morrey, M	Aspinwall & Co
Moss, C	National Association of Waste Regulation Officers
Moss, A	South Staffordshire Water plc
Moss, C	Shropshire Country Council
Munro, S	British Gas Properties
Murphy, C	Institute of Wastes Management
Murray, A	Staff. County Council
Neillie, G	Gleneagles Spring Water
Newbold, C	English Nature
Newton, J R	Hertfordshire County Council
Nisbet, T	Forestry Authority
Norton, C	Anglian Water Services
O'Riordan, N	Ove Arup and Partners
Packman, M	Southern Science
Pain, A	Fife Regional Council
Palmer, R C	Soil Survey & LRC
Payne, M	National Farmers Union
Peters, C J	LWRA
Philp, R	NE Fye District Council
Piper, B	GU Projects
Plant, D	Grampian Regional Council
Pollock, D T	BACMI
Poodle, T	Clyde River Purification Board
Price, B	Anglian Water Services
Price, M	University of Reading
Price, S	Friends of the Earth
Proctor, W	Tay River Purification Board
Prosser, H J	Welsh Office
Pugh, K	NE River Purification Board
Purdie, L	Fife Regional Council
Rudd, P W	Biwater Europe Ltd
Read, D	WS Atkins Environment
Reeve, C E	HR, Wallingford
Rendall, R P	Grampian Regional Council
Riby, J	Scarborough Borough Council
Robins, N S	British Geological Survey
Robson, A	East Sussex County Council
Rodgers, R I	Severn Trent Water Ltd
Sargent, R J	Forth River Purification Board
Saville, D R	DOE (NI)
Schooling, C	Dumfries/Galloway Reg Council
Selley, C D	Silica and Moulding Sands Association
Selwyn, J	UK CEED
Shaw, P J	NRA Southern
Sheils, T	Department of the Environment
Skinner, A	Severn Trent NRA
Smith, E	Anglian Water Services
Smith, K	University of Stirling
Smith, H	Clyde River Purification Board
Smith, A	TARMAC Roadstone Ltd
Smith, E J	Anglian Water
Smith, D W	Pick Everard
Smith, J A	Whelan
Smith, D	GU Projects
Smith, A J	Sutton District Water
Smyth, P	National Farmers Union
Spence, I	University of Abertay
Stebbing, G K	BOC Ltd
Stevenson, M W	Southern Testing Laboratories
Stewart, J	Questor
Street, E	Kent County Council
Taylor, W	Highland Regional Council
Taylor, J	British Waterways
Tervet, D J	Solway River Purification Board
Thairs, E T	Water Services Association
Thatcher, J P	Mid Kent Water plc
Try, D E	East Surrey Water plc
Tubb, C	South West NRA
Turl, L A D	SOAFD
Vaughan, J	Department of the Environment
Vinter, A	SAC
Walker, B	Pollution Control Engineering
Ward, D W	UKASTA
Wardlaw, R	University of Edinburgh
Waterworth, J	DoE (NI)
Waygood, S	National Power plc
Werritty, A	University of Dundee
Wheater, H S	Imperial College
White, H	Peak District National Park
White, I	National Association of Waste Regulation Officers
Wilkins, R E	East Sussex County Council
Wilkinson, V G	Walsall MBC
Willey, R J	Centre for Env. & Waste
Williams, H J J	Dean and Chapter of Durham
Wilson, K S	SAGA
Wilson, M J	MLURI
Wolstenholme, R	WRC
Wood, C	AEA
Woods, A	Country Landowners Association
Wright, P	SOED
Wright, C	Department of the Environment
Wu, K	University of Glasgow

Glossary

Permeability	Measure of the ability to transmit water
Database	Collection of structured data independent of any particular application
Expert systems	Computer programs that aim to use knowledge and formal reasoning techniques to solve problems to give advice
Decision support system (DSS)	Interactive computer-based system that helps decision makers utilise data and models in the solution of unstructured problems
Dose	Mass of pollutant
Geographical information system (GIS)	Database management system that handles features, normally found on a map, in a graphical form on computer monitor
Issue	A threat to groundwater quality and quantity; constraint on groundwater development; any significant uncertainty concerning groundwater
Knowledge base	A component of a decision support system comprising information, such as rules and regulations
Kriging	A geostatistical technique for exploiting spatial correlations
Model base	A component of a decision support system comprising a variety of tools, most commonly predictive computer models
Perspective	The view of an 'issue' taken by a particular institution or group of institutions
Porosity	Proportion of void space in a rock
Porosity, drainable	That part of the porosity that will drain under gravity (a function of pore connectivity and size)
Risk assessment	Characterisation of the potential adverse affects of exposure to hazards
Risk management	Process of evaluating alternative regulatory actions and selecting among them
Stakeholders	All parties who have responsibility for, or interest in, groundwater development
Underpinning science	The underlying combination of hydrogeological processes, data and databases, and models