GROUNDWATER IN THE UK

GROUNDWATER ISSUES

Quality . Quantity . Sustainability

FWR

Natural Environment Research Council

NRA

Sniffer
SCOTLAND & NORTHERN IRELAND FORUM FOR ENVIRONMENTAL RESEARCH

Water Services Association

The Water Companies' Association

UK Groundwater Forum

September 1995
FR/GF 2

INFOWORDS Research Report Summaries Database

Research Category:
Environmental
Strategy

GROUNDWATER IN THE UK

A STRATEGIC STUDY

GROUNDWATER ISSUES

FR/GF 2

SEPTEMBER 1995

Report prepared by:

British Geological Survey
Maclean Building
Crowmarsh Gifford
Wallingford
Oxfordshire
OX10 8BB
UK

Tel: 01491 692 351
Fax: 01491 692 345

to whom technical enquiries should be addressed.

Published by:
Foundation for Water Research (FWR),
Allen House, The Listons,
Liston Road, Marlow, Bucks SL7 1FD, UK

Telephone: (01628) 891 589
Fax: (01628) 472 711

Price: £15.00 (20% discount to FWR Members)

Further copies can be obtained from FWR

This report is published on behalf of the joint sponsors listed below:

Foundation for Water Research
National Rivers Authority
Natural Environment Research Council
Scotland and Northern Ireland Forum for Environmental Research
Water Services Association
Water Companies Association

UK GROUNDWATER FORUM

One of the key recommendations of the Groundwater Strategy Study was that the dialogue and consultation achieved during the study should be maintained and extended through a Groundwater Forum.

The objectives of the Forum are to:

- promote discussion of the issues associated with the sustainable exploitation of groundwater resources;
- encourage co-ordinated action to address the issues;
- ensure widespread dissemination of information about groundwater;
- improve public understanding of the importance and significance of groundwater as a sustainable resource;
- seek a consensus on policy approaches to groundwater management.

GROUNDWATER ISSUES

Editor

D G Kinniburgh, BGS

Strategic Study Coordinator

D R C Grey, BGS

Authors

B Adams, BGS
J A Barker, BGS
P Bishop, Mott MacDonald
D K Buckley, BGS
P J Chilton, BGS
M B Crawford, BGS
W G Darling, BGS
W M Edmunds, BGS
I N Gale, BGS
K Gilman, IH
A Gustard, IH
R C Harris, NRA
P Howsam, Silsoe College
D G Kinniburgh, BGS
A R Lawrence, BGS
T R Nisbet, Forestry Authority
N S Robins, BGS
M E Stuart, BGS
C Tubb, NRA
J M West, BGS
G M Williams, BGS
A R Young, IH
P L Younger, University of Newcastle

CONTENTS

OTHER ISSUES (continued)

INTRODUCTION

This set of papers provides the background to the 31 groundwater issues raised in the report '*Groundwater in the UK: A Strategic Study - Issues and Research Needs*'. The *Strategic Study* summarizes what is known about the United Kingdom's groundwater resources and what is not known but needs to be known in order to manage the water resources in a responsible and sustainable way. The *Strategic Study* deliberately focused on the *issues* facing groundwater management: an *issue* was defined as a

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

The study also identified a priority agenda for the groundwater research that needs to be undertaken in order to make progress in tackling the various issues that were identified.

A specific objective of the Study was to seek the views and participation of the main stakeholders in groundwater in the UK. These included the water utilities, regulators, industry conservation bodies, various Government Departments and the research community. The consultations were carried out through four main devices: a mailshot, individual consultation meetings, a UK Groundwater Forum, and national seminars held in England (for England and Wales) and Scotland (for Scotland and Northern Ireland). As a result of these early consultations, a wide-ranging list of issues was prepared which was eventually reduced to 31 of which 14 were considered to be 'Major'. The priorities for R & D were also discussed by representatives of the groundwater research community at a Science Seminar held in Wallingford on 20th January 1995.

It was decided to prepare reviews summarizing the current status of each of the various issues and to identify the main R & D requirements. These reviews became known as the 'Issues Papers'. A structured approach was adopted in order to provide some uniformity to the reviews. Each paper is divided into the following headings:

Problem status:	A brief statement of the issue as related to its impact on groundwater
Trends:	Is the issue getting better, worse or not changing?
Context Changes:	What are the likely changes in legislation etc that may change the importance of the issue?
Learning Curve:	A brief summary of our existing knowledge
Perspectives:	The views of various interested parties
Benefits and Beneficiaries:	What are the benefits of reducing the problem and who benefits?
Response:	The recent response to the problem
R & D:	A bulleted list of the R & D required to advance our understanding of the problem
References:	A brief list of key cited references.

The majority of these Issues Papers were initially drafted by members of BGS but where outside experts were willing they were invited to contribute as lead authors or co-authors. The early drafts were circulated for comment to those who had expressed an interest in reviewing them. This review process drew a wide response and led to a considerable improvement in the text. The authors and reviewers are given at the end of each paper. We have attempted to identify all of those who contributed to this review process but in some cases responses were received anonymously and so it has not been possible to acknowledge all reviewers. We apologise to any whose names have been inadvertently omitted. Sometimes reviewers had very different perceptions of how a particular issue should be addressed or of how it is perceived by others. The authors had the difficult task of trying to reconcile these differences and have tried to achieve a fair balance.

Although we have tried to anticipate the impact of future changes in the groundwater environment and in the legislative programme that protects it, we are aware that this is a fast moving field and one that is currently in the state of considerable flux. The proposed merging of the regulatory functions of the NRA, HMIP and the WRAs into a single Environment Agency is one obvious example. Therefore the reviews may have a limited 'shelf life' especially in their more speculative parts. Nevertheless we hope that they provide a useful review of the current issues for UK groundwater and of the research that is needed to underpin the future sustainability of it.

The issues are divided into **MAJOR** issues and **OTHER** issues on the basis of the responses received during the consultation process that formed the early part of the Strategic Study. Other than that, the issues are arranged in alphabetical order.

D G Kinniburgh
D R C Grey

Wallingford
June 1995

ACRONYMS AND ABBREVIATIONS

AMD	Acid mine drainage
AMPs	Asset Management Plans
ARBRE	Forestry Project
AWWARF	American Water Works Association Research Foundation
BGS	British Geological Survey
BOD	Biochemical oxygen demand
BRE	Building Research Establishment
CAP	Common Agricultural Policy
CATCHIS	A CATCHment Information System
CBI	Confederation of British Industry
CCIRG	Climate Change Impacts Review Group
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act (USA)
CFCs	Chlorinated fluoro-carbons
CHEMSAFE	Saftey Campaign
CIRIA	Construction Industry Research and Information Association
CIS	Countryside Information System
CPRE	Council for the Protection of Rural England
CQA	Construction Quality Assurance
CRU	Climatic Research Unit
DOC	Dissolved organic carbon
DoE	Department of the Environment
DoE(NI)	Department of the Environment (Northern Ireland)
DTI	Department of Trade and Industry
DWI	Drinking Water Inspectorate
EC	European Commission
ECN	Environmental Change Network
EPC	Equivalent porous continuum
ESA	Environmentally Sensitive Area
ET	Environmental Technology
ETSU	Energy Techn. Support Unit
EU	European Union
FLOWPATH	Groundwater Model
FWR	Foundation for Water Research
GCMs	General Circulation Models
GIS	Geographical Information System
HLW	High-level waste
HMIP	Her Majesty's Inspectorate of Pollution
HMSO	Her Majesty's Stationery Office
IEHO	Institution of Environmental Health Officers
IH	Institute of Hydrology
ILW	Intermediate-level waste
IPC-MS	Inductively coupled plasma-mass spectrometer
IPCC	Intergovernmental Panel on Climate Change
ITE	Institute of Terrestrial Ecology
IWEM	Chartered Institution of Water and Environmental Management
KIWA	Netherland Institute for Water Research
L(D)NAPLs	Light (dense) NAPLs
LLW	Low-level waste
LOIS	Land-Ocean Interaction Study
LURFEX	NERC Land use Foresight Exercise
MAFF	Ministry of Agriculture, Fisheries and Food
MODFLOW/ MODPATH	Groundwater models
MRC	Medical Research Council
MTBE	Methyl tertiary butyl ether
NAPLs	Non-aqueous phase liquids
NATO	North Atlantic Treaty Organisation
NCC	Nature Conservancy Council
NELUP	NERC/ESRC Land Use Programme
NERC	Natural Environment Research Council
NFFO	Non-Fossil Fuel Obligation
NFU	National Farmers Union

NRA	National Rivers Authority
NRPB	National Radiological Protection Board
NSA	Nitrate Sensitive Area
NVZ	Nitrate Vulnerable Zone
ODA	Overseas Development Association
PFA	Pulverised fuel ash
PHABSIM	Low Flows Model
R & D	Research and Development
RCRA	Resource Conservation and Recovery Act (USA)
RPB	River Purification Board
RWAs	Regional Water Authorities
SPRAYSAFE	Safety Campaign
SRC	Short-rotation coppice
SSLRC	Soil Survey and Land Research Centre
SSSIs	Sites of Special Scientific Interest
TBME	see MTBE
THORP	Thermal Oxide Reprocessing Plant
TIGER	NERC Terrestrial Initiative in Global Environment Research
UK WIRL	United Kingdom Water Industry Research Ltd
UK	United Kingdom
US EPA	United States Environmental Protection Agency
UWWT	Urban Waste Water Treatment
VOCs	Volatile organic compounds
WHO	World Health Organization
WMO	World Meterological Organization
WMP	Waste Management Paper
WRA	Waste Regulation Authority
WRc	Water Research Centre

MAJOR ISSUES

ACID MINE DRAINAGE

PROBLEM STATUS

The principal problem created by uncontrolled mine drainage is that of acid mine drainage (AMD). Acid mine drainage is known world-wide as a major cause of water quality degradation. The high metal concentration and low pH have serious consequences on the ecological and resource value of surface waters. In the UK, discharges from active mines are controlled by systems of "consents", which generally demand sufficient treatment of waters that AMD is not a problem. Opencast mines (both active and reclaimed) are also subject to stringent control and consequently cause few long-lasting AMD problems.

However, in areas where groundwater rebound has occurred after abandonment of deep mines, AMD pollution is widespread and serious. Geotechnical problems associated with groundwater rebound include subsidence (from collapse of shallow bord-and-pillar workings destabilised by inflowing water), slope failures, temporarily increased methane and carbon dioxide emissions (forced up by rising water), corrosion of Portland cement-based structures by sulphate-rich waters and inundation of landfills.

RELATED ISSUES

Acidification
Rising water levels

TRENDS

Interest in hydrogeological aspects of AMD in Britain first arose in response to the waves of colliery closures in outlying coalfields in the 1960's and 1970's, leading to investigations in Scotland (Robins, 1990) and the Forest of Dean (Aldous *et al.*, 1986). Two recent developments have rekindled national interest in AMD arising from groundwater rebound in abandoned deep mines:

(i) The spectacular outburst of ochreous water from the Wheal Jane tin mine in Cornwall in January 1992 (NRA, 1994).

(ii) Predictions of widespread AMD in the wake of recent abandonment of major coalfields in northern England (Younger, 1993).

The indications are that groundwater rebound will lead to AMD pollution of surface waters and of aquifers which overlie the Coal Measures (eg the Permian Magnesian Limestone and Basal Sands and the Triassic Sherwood Sandstones). Timescales for onset of pollution vary greatly from area to area, generally depending on variations in rainfall, the extent of interconnected old workings and the depth below some suitable surface discharge point (eg a river valley) to which groundwater levels were depressed during dewatering.

Thus in the incised landscape of South Wales, the cessation of pumping at Blaenant in 1991 led to surface discharge into the Neath Canal in around 18 months; at the other extreme, time-scales of 30 to 40 years are predicted for full rebound in the Durham coalfield, which is interconnected at depth over distances in excess of 50 km (Sherwood and Younger, 1994). Without preventative pumping, or expensive treatment of future discharges using active or passive methods (NRA, 1994), increasingly widespread pollution seems inevitable over the next few decades. Geotechnical problems, though less visible and more sporadic in their occurrence, can similarly be expected to occur more frequently.

CONTEXT CHANGES

Implementation of statutory water quality objectives (in response to EC legislation) is raising interesting questions about responsibility for AMD from abandoned mines. Pilot projects to passively treat AMD using constructed wetlands are being implemented at Wheal Jane (with DoE funding) and in the Afon Pelenna catchment, West Glamorgan (with EC LIFE funding). However, there is no general source of funding to deal with major AMD discharges. Anticipated changes in UK law during the establishment of the proposed Environmental Agency may address this problem. The British coal industry is in a state of flux, ie with the sell off of British Coal and the creation of the Coal Authority, consequently responsibilities for AMD from abandoned mines are also likely to remain unresolved in the immediate future.

Under the Water Resources Act 1991, discharges from abandoned mines are treated differently from all other classes of discharge in the statutory protection that they enjoy. There is a specific defence that renders the NRA unable to prosecute anyone permitting (as distinct from causing) a polluting discharge to flow from an abandoned mine. It is also likely that mine operators will have to give the Environment Agency (as successor to the NRA) six months' notice of any proposed abandonment in order to ensure that the full effects on the water environment can be responsibly assessed.

LEARNING CURVE

The root cause of AMD is oxidation of sulphide minerals, particularly pyrite, which is facilitated on a large scale by dewatering and ventilation for mining. The main manifestations of AMD are high metal concentrations, especially of iron, which forms the thick ochre deposits typical of AMD, high sulphate, presence of trace metals, and in many cases high acidity though, paradoxically, much "AMD" is alkaline at the point of emergence.

Much research has been undertaken into the pyrite oxidation process, and the modern consensus is that:

(i) oxygen and moisture are essential to initiating the reaction
(ii) rapid oxidation only occurs with bacterial catalysis
(iii) fine-grained pyrite (eg framboids) is most reactive.

Natural geochemical processes which serve to ameliorate AMD are less well understood, but clearly include neutralisation by dissolution of carbonate minerals or mixing with buffered groundwaters, bacterial sulphate reduction (which also generates alkalinity), and precipitation of complex hydroxide and sulphate minerals which serves to decrease the dissolved solids content, but can lead to blanketing of the beds of receiving waters, destroying important econiches.

Most hydrogeological analyses of groundwater rebound in abandoned mines have adopted the equivalent porous continuum (EPC) approach to modelling, whereas non-Darcian flow is expected in many underground workings (Sherwood and Younger, 1994). For regional analyses the EPC approach may give satisfactory results, but is likely to break down where local flow paths are modelled. Coupled modelling of flow and chemistry for abandoned deep mines has yet to be explored. Research into geotechnical problems associated with groundwater rebound in mined areas has been largely descriptive to date.

PERSPECTIVES

In the UK, current AMD affects local authorities, the NRA/RPB's, some water companies, farmers and the owners and users of riparian fishing rights. Future AMD will affect all of the above groups, and could also cause serious problems for previously unaffected water companies such as Severn Trent and North East Water. Geotechnical problems will impact local authorities, insurance companies and individual land-owners. However, there are very limited data, and the timescale for change is small given the long history of pumping.

BENEFITS AND BENEFICIARIES

Safeguarding the environment, protecting aquifers and preventing deterioration of underground structure.

RESPONSE

The UK response to AMD is currently in a state of turmoil. Substantial indemnity is afforded in the Water Resources Act 1991 and in Section 23 of the Control of Pollution Act 1974 in Scotland to those who "permit" pollution from abandoned mines. Lobbying by coalfield communities, water companies, the NRA and local authorities has so far failed to achieve changes in this law. In a recent consultation paper, *Paying for our Past*, Government said that it would reassess the justification for these unique statutory exemptions and it now appears likely that the defence for permitting pollution from abandoned mines will be removed in the new Environment Bill, but only for mines abandoned after 1999, leaving the position regarding old mine discharges essentially unchanged. At present an uneasy truce prevails under the terms of a "Memorandum of Understanding" between British Coal and the NRA (see NRA, 1994), which provides for consultation between the two parties before substantial changes in minewater management are implemented. In the meantime, the NRA/RPB's and local authorities respond to new outbreaks of AMD on an *ad hoc* basis. The future status of British Coal's traditional responsibility for mining subsidence is also uncertain, but seems likely to remain with the Coal Authority.

R & D

- carry out a broad survey of the scope and scale of the AMD problem and identifying areas where adjacent aquifers will be affected and possible acidification 'hotspots' (including an evaluation of the risks and timescale posed by the AMD problem)
- improve understanding of the mechanics of flow in abandoned mines by monitoring and modelling
- investigate the geochemical processes occurring during generation and subsurface transport of AMD
- develop coupled models of flow and chemistry in abandoned deep-mined strata
- carry out a rigorous analysis of geotechnical problems arising from groundwater rebound in abandoned mines
- apply appropriate models to optimise water management in abandoned deep-mined strata
- design, monitoring and optimisation of minewater management infrastructure, including pumping systems and constructed wetlands.

REFERENCES

Aldous, P. J., P. L. Smart and J. A. Black (1986). Groundwater Management Problems in Abandoned Coal-Mined Aquifers: A Case Study of the Forest of Dean, England. *Quart. J. Eng. Geol.* 19: 375-388.

NRA (1994). *Abandoned Mines and the Water Environment.* Report of the National Rivers Authority. Water Quality Series No 14. London: HMSO. 46 pp.

Robins, N. S. (1990). *Hydrogeology of Scotland.* British Geological Survey. London: HMSO. 90 pp.

Sherwood, J. M. and P. L. Younger (1994). Modelling Groundwater Rebound after Coalfield Closure: An Example from County Durham, UK. *Proceedings of the 5th International Minewater Congress, Nottingham, UK* (in press).

Younger, P. L. (1993). Possible Environmental Impact of the Closure of Two Collieries in County Durham. *J. Inst. Water & Env. Mgmt.* 7: 521-531.

Author: P L Younger, University of Newcastle

Reviewers: N S Robins, BGS
D G Kinniburgh, BGS
A R Agg, FWR
J Aldrick, NRA
P Walmsley, Forth RPB

AFFORESTATION

PROBLEM STATUS

Afforestation, and deforestation, can have important long-term impacts on water resources and water quality. These impacts have been most widely studied for surface waters in the uplands where most afforestation has taken place. The interception loss from coniferous plantations is large and can double the amount of evaporation from a forested catchment compared with a non-forested catchment. This will lead to reduced streamflow. Similar reductions would also be expected for groundwater recharge but since most of the major UK aquifers are situated in the lowlands, the problem does not arise in the same way. In addition to the lower interception losses due to the drier and less windy climate in the lowlands, conifer forests comprise a relatively small proportion of lowland land use.

However, in recent years, the planting of broadleaf woodland in the lowlands has increased, often on former farmland. In areas overlying aquifers, current best estimates suggest that planting on arable land will give rise to slightly less groundwater recharge while that on grassland could give rise to an increase in recharge. These estimates are based on relatively few studies and much uncertainty remains regarding the influence of tree, crop and soil type, woodland structure and regional climate. Recent interest in the growing of short-rotation coppice for energy production has also raised new questions about the water use of these plantations and the extent of nitrate leaching beneath them.

Since pesticide and fertilizer applications are normally considerably lower on forested land compared with most farmland, any increase in lowland afforestation is likely to lead to improved water quality as a result of reduced concentrations of pesticides and nitrate infiltrating to the groundwater.

RELATED ISSUES

Geochemical baseline change
Land-use change
Nitrate

TRENDS

Several centuries of deforestation have resulted in the UK (24.1 M ha) having one of the lowest proportions of land under forest in Europe. This trend was reversed in the middle part of this century following the setting up of the Forestry Commission in 1919. Since then there has been a steady expansion of the forest area (currently 10% of land), with the planting of predominantly conifer forests in upland areas. However, in recent years there has been a shift in emphasis towards increased planting of broadleaves which currently account for about 60% of all new plantings. 220,000 ha of new woodland have been planted in the last ten years with 80% of this being carried out by the private sector. In 1994, 17,300 ha of new planting took place of which 92% was by the private sector and 8% by the Forestry Commission (Forestry Commission, 1994). 16,500 ha of existing woodland was also restocked. The current forest policy (Forestry Commission, 1991) identifies as its two main aims:

(i) "the sustainable management of our existing woods and forests";
(ii) "a steady expansion of tree cover to increase the many, diverse benefits that forests provide".

Long-term changes in land use, such as afforestation, are strongly influenced by the prevailing economic and fiscal incentives. They are therefore difficult to predict. The general feeling is that there will continue to be a steady annual increase in the area under trees, and that new plantings will be predominantly by private individuals as opposed to the Forestry Commission.

CONTEXT CHANGES

Several factors will affect the type, amount and location of new forest planted:

- **Fiscal incentives.** Tax concessions (now repealed) played an important part in increasing the amount of tree planting in the 1980's, especially on marginal land.

- **Grants.** A number of grants are currently available to assist in tree planting. These include the Woodland Grant Scheme run by the Forestry Authority and the Farm Woodland Premium Scheme run by MAFF and the respective Agriculture Departments in Scotland and Northern Ireland.

- **CAP reform.** At the time of writing (December 1994), land which is taken out of production to plant trees under the Farm Woodland Premium Scheme cannot count towards a farmers set-aside obligation. The Government has been pressing for this to be changed and the Forestry Commission have now produced a report and are due to bring a proposal to amend the rules shortly.

- **Energy forestry.** Short-rotation coppice (SRC) of poplar and willow is a potential form of renewable energy with a payback of some 20 to 30 times in energy terms. An incentive for SRC planting is the Non-Fossil Fuel Obligation (NFFO) which guarantees premium rates for the electricity produced. The third tranche of the NFFO was announced on 20 December 1994 and included three wood gasification projects based on SRC. The largest of these, the £26M ARBRE project proposed by Yorkshire Water's waste management and environmental services offshoot, is expected to need about 2,000 ha of SRC to supply a 8 MW plant. The cost of energy from SRC is still relatively high compared with other forms of renewable and non-renewable energy.

- **Community Forests and National Forests.** Community Forests are a joint initiative between the Forestry Authority, the Countryside Commission and local authorities to increase tree planting in neglected areas close to conurbations with a long industrial history. Twelve such forests, each covering 10-15,000 ha each, have been designated. These 'forests' would be made up from a mosaic of smaller plantations and are planned to cover only about 30% of the designated area. They are likely to comprise predominantly broadleaved species and are intended to be multifunctional. A new National Forest in the Midlands has also been approved. This will cover about 500 km^2.

- **Global issues.** An increase in the use of wood as a fuel would help to satisfy international undertakings on reducing (or stabilizing) carbon dioxide, sulphur dioxide and nitrogen oxides emissions (as promised at the Rio Summit). A carbon tax would provide an incentive for wood-for-fuel production. Britain currently imports 85% of its timber requirements.

LEARNING CURVE

Most studies of the impact of afforestation on UK water resources have been concerned with the impact on surface waters since traditionally the majority of planting has occurred in the uplands where surface drainage predominates. Water yields from catchments containing closed canopy conifer forest are usually less than from moorland or grassland catchments due to their greater interception loss. This loss increases with forest height and canopy development and is greater in the wetter, upland areas of Britain (Calder, 1990). Though assessments of the degree of reduction in a given catchment cannot be exact, research suggests that there may be some 1.5-2.0% reduction of potential yield for every 10% of a catchment under mature conifer forest (Forestry Commission, 1993). Water yields from young forests or felled areas are unlikely to differ significantly from moorland catchments.

Studies at Plynlimon, Wales (Kirby *et al.*, 1991) where there are twinned forested and non-forested catchments have shown that there is about twice as much evaporation from a forested (coniferous) catchment compared with an adjacent moorland catchment.

The difference in water yield between mature forest and grassland in the lowlands is less than that in the uplands. This is because of the drier and less windy climate which reduces the importance of the interception loss. However, changes in the amount of net rainfall in the lowlands will have a relatively large effect on groundwater recharge since the absolute amount of recharge is low.

There have been several detailed studies of evaporation from conifer and broadleaved forests in southern Britain by the Institute of Hydrology - especially at Thetford (Norfolk), Black Wood (Hampshire) and Old Pond Close

Table 1. Pore water nitrate-N concentrations in the Chalk unsaturated zone (2-10 m) beneath beech at Black Wood, Hampshire (from Harding et al., 1992)

Site	Average pore water NO_3-N (mg/l)
Beech, centre of forest	9.3
Beech, W edge (<50 m)	1.4
Beech, E edge (<50 m)	12.7
Ash, centre of forest	1.2

(Northamptonshire) and these give some indication of the magnitude of effects likely to be found in found in lowland Britain. Table 1 illustrates some recent results for ash and beech at Black Wood (on chalk) and ash at Old Pond Close (on clay) based on detailed field measurements. The low values for evaporation from wheat may be an underestimate since the model used assumes very low evaporation in the winter (10% of Penman ET).

As can be seen from Table 1, the trees at these sites evaporate less water than permanent grassland largely because of the shorter growing season of the trees. However, they appear to evaporate more water than the wheat. Evaporation from the beech was also greater than from the ash. In wetter parts of Britain, such as in the south west, interception losses will be greater and broadleaf trees may use more water than grassland.

The soil type and geology is also important. Grass growing on a chalk soil rarely suffers water stress and so continues to evaporate at close to potential evaporation rates in dry years whereas on a clay soil, evaporation from grass is considerably less. The grass tends to respond by going to seed and dying off above ground - an option not available for trees. This accounts for the lower evaporation from grass at a site with the soil (clay) and climate characteristics of Old Pond Close compared with that from a site like Black Wood which is on chalk. Therefore while this reduction in evaporation is a significant factor for grassland in most years, this is only true for forests in very dry years. Hence the small difference between the estimates for evaporation from ash at the two sites (Table 1).

Relatively little is known about evaporation from conifers in the lowlands but calculations for Thetford forest (sandy soil over chalk) suggest that evaporation is likely to be up to 200 mm greater from conifers than from ash and so there is little doubt that an extensive plantation of conifers would lead to a significant reduction in groundwater recharge (Cooper and Kinniburgh, 1993). Replacing grass with ash under similar conditions would be likely to lead to an increase of between 10 and 100 mm/a in groundwater recharge. In general, the amount of groundwater recharge can be ranked in the following sequence:

winter wheat > ash > grass > conifer

Pore water nitrate profiles from the unsaturated zone at Black Wood (Table 2) showed that on average the concentration of nitrate leaching beneath the beech was 9.3 mg/L NO_3-N equivalent to leaching of about 30 kg N/ha/a. A distinct 'edge' effect was found at the exposed westerly edge with lower-than-average nitrate leaching. Nitrate concentrations beneath clearings in the beech where trees had died or suffered windthrow indicated that nitrate leaching could exceed 50 kg N/ha/a in places, comparable to that under much arable land. Nitrate leaching beneath the ash at Black Wood (Table 2) was much lower than under the beech perhaps because the ash, unlike the beech, had a dense understorey.

Most studies of forest evaporation have taken place well away from the margins of woods and plantations. It is quite possible that evaporation at forest edges could be greater than in the interior. This could be significant if new forests are created as a mosaic of smaller plantings.

Table 2. ANNUAL RAINFALL AND ESTIMATED EVAPORATION (IN MM/A) AT TWO SITES IN SOUTHERN BRITAIN (AFTER HARDING ET AL., 1992).

Site (dates)				
	Evaporation			
Rain	Grass	Wheat	Beech	Ash
Black Wood, Hants (1967 - 86)				
740	468	378	423	399
Old Pond Close, Northants (1970 - 86)				
589	418	319	-	394

PERSPECTIVES

Although a number of incentives in the form of grants are available to encourage tree planting, the evidence so far is that the amount of new planting is falling well behind the targets set. This may reflect the reluctance of private landowners to invest in forestry given the long-term commitment required.

If afforestation has a significant impact on the amount of groundwater recharge then this would be of interest to both the water regulators and the water undertakers. The generally good quality of water recharging beneath forests is beneficial to the long-term water quality in the groundwater catchment. Any changes in groundwater levels brought about by afforestation near coasts could impact on the extent of saline intrusion.

BENEFITS AND BENEFICIARIES

Any major change in land use, such as an increase in lowland afforestation or the growth of energy forestry, will have an impact across many organizations and government departments. The water industry needs to know the impact of afforestation on the quantity and quality of groundwater recharge under forests. In general, forests can be viewed as a long-term, assured source of good quality groundwater and therefore something to be encouraged. For example, this groundwater could be used for blending with poorer quality water. Afforestation could also be beneficial in source protection areas close to water supply boreholes especially where existing groundwater nitrate concentrations are high.

RESPONSE

The water industry has taken a long-term interest in the impact of afforestation on water resources and in the past, the DoE has sponsored much of the forest hydrology research carried out in the UK. The Forestry Commission has also been an important contributor to forest hydrology and in 1988 produced 'Forest & Water Guidelines' to help foresters adopt best practices in the management of forests. These Guidelines are regularly under review and the third edition is now available (Forestry Commission, 1993). Formal environmental assessment procedures for new woodland were introduced in 1988. These allow the Forestry Authority to assess the effect of afforestation on the environment, including the water environment. Grant applications, for example to the Woodland Grant Scheme, are now vetted for their environmental impact.

Relatively little forest hydrology research has been funded in the lowlands due to the long-held view that lowland forestry has a relatively benign influence on water resources. However, the Forestry Commission has recently sponsored Alice Holt Forest as a terrestrial site in the Environmental Change Network. There is also some on-going research into the possible impact of short-rotation coppice (SRC) of poplar and willow on water resources. These fast-growing trees have a reputation for a high water demand. SRC plantations, if located near to a sewage treatment works, also offer the possibility of being used for sludge applications. This has attracted the attention of some water undertakers in both England and Scotland.

R & D

- improve process models for conifer and broadleaf forest evaporation based on theoretical studies with calibration against field studies for different species and different forest structures.
- establish extent of recharge under various climates, broadleaf species and soil types for both major and minor aquifers. There is a particular need for studies on the Sherwood (Triassic) Sandstone aquifer where some of the new planting will take place.
- investigate influence of forest size and the mosaic structure of many new forests on recharge and water quality including any 'edge' effects.
- quantify nitrate leaching under a variety of conifer and broadleaf species at various stages of the forest management cycle.
- quantify the extent and consequences of continued soil acidification on groundwater (including the application of the 'critical loads' approach).
- evaluate impact of various forest management strategies (pesticides and sewage sludge applications) on groundwater quality.

REFERENCES

Calder, I. R (1990). *Evaporation in the Uplands.* Chichester: John Wiley.

Cooper, J. D. and D. G. Kinniburgh (1993). *Water resource implications of the proposed Greenwood Community forest.* NERC/NRA.

Forestry Commission (1991). *Forest policy for Great Britain.* Edinburgh: Forestry Commission.

Forestry Commission (1993). *Forests & Water Guidelines.* HMSO: London.

Forestry Commission (1994). *Facts and Figures 1993-1994.* Edinburgh: Forestry Commission.

Harding, R. J., R. L. Hall, C. Neal, J. M. Roberts, P. T. W. Rosier and D. G. Kinniburgh (1992). *Hydrological Impacts of Broadleaf Woodlands: Implications for Water use and Water Quality.* **NRA Project Report 115/03/ST.** Bristol: National Rivers Authority.

Kirby, C., M. D. Newson and K. Gilman (1991). *Plynlimon research: The first two decades.* **Report 109**. Institute of Hydrology, Wallingford.

Authors: D G Kinniburgh, BGS
T R Nisbet, Forestry Authority

Reviewer: R L Hall, IH

CONTAMINATED LAND

PROBLEM STATUS

The Environment Bill defines contaminated land as "any land appearing to a local authority to be in such a condition, by reason of substances in, on or under the land that harm or water pollution is being, or is likely to be caused". Other countries and bodies have used different definitions but the terminology in UK legislation will by necessity be distinctive.

The impact of contaminated land on groundwater is of concern from two reasons: (i) the groundwater contained within contaminated land may be contaminated and may migrate away from the site, and (ii) the soils at or near the surface may provide a source of soluble contaminants which may leach to the groundwater and then migrate off-site (Harris and Flavin, 1991; Harris and Gates, 1993).

Contaminated land arises largely as a result of past industrial processes which have left behind a legacy of substances including tars and oils, metals, organic compounds and soluble salts (House of Commons, 1989). These can give rise to a range of liquid, solid and gaseous contaminants, which can affect the health of people on and close to the land itself and the structures of buildings. The more soluble and mobile contaminants can be transported below and away from the contaminated land and may cause serious quality problems for surface water and/or groundwater (National Rivers Authority, 1994). In the case of groundwater, industrial sites may have significant plumes of contaminated water under and moving away from them, even though little in the way of contaminated land remains at or close to the surface. Although much contaminated land is situated in urban industrial areas, other activities, particularly mining, landfill sites and military installations, have produced contaminated sites in more remote rural situations.

The UK government has not sought to provide the type of comprehensive national assessment of contaminated land that has been carried out by some of our European partners, eg the Netherlands, Denmark, Finland, Norway etc (Visser, 1993). Using studies of more limited scope, particularly in Wales, taking account of surveys of derelict land and drawing on the experience of other European countries, several sources have suggested there could be some 50,000 potentially contaminated sites in the UK, affecting about 50,000 ha of land or some 0.5% of the total land area. However, only a very small number of these are likely to present an immediate threat to public health or the environment, and only a proportion present a risk of groundwater or surface water pollution. There are particular risks from the redevelopment of sites where disturbance may release and re-mobilise pollutants.

RELATED ISSUES

Landfill
Remediation
Rising water levels
Sewers, soakaways and septic tanks

TRENDS

Without a national picture of the extent (the scale) of the problem or of the nature of the problem with respect to the potential impact of contaminated land on surface water and groundwater, it is difficult to provide any indications of trends. Only a proportion of the contaminated sites have an impact on water quality, and the NRA has begun to assess the extent and distribution of such sites. Obtaining a comprehensive picture of the nature of the problem requires knowledge of the types and amounts of contaminants to be found at each site. From this, it is important to be able to identify which sites are causing breaches of existing water quality standards and which would cause breaches of future water quality objectives, if statutory objectives were set. These are likely to be defined in relation to end use and/or off-site contamination only. The nature of contamination at each site is also required to allow an economic assessment of remediation to be made, and the most seriously contaminated sites prioritised for action. Only when this information is collected and regularly updated can detailed trends be observed.

CONTEXT CHANGES

Contaminated land has become a high profile environmental issue within the last five years. The introduction of the Environmental Protection Act in 1990 envisaged, among other provisions, that local authorities would compile and maintain under Section 143 of the Act a national register of all land put to contaminative use. In response to strong lobbying from vested interests, and general concern about the threat of "blight" on registered land, the government then put forward proposals in 1992 for a more restricted register, and then in March 1993 withdrew all proposals for registration. The powers of local authorities have been redefined in the new DoE guidance "Framework for Assessing the Impact of Contaminated Land on Groundwater and Surface Water" (Department of the Environment, 1994). Local authorities can compile their own registers, will have powers to investigate contaminated land and will require its remediation under the new legislation currently within the Environment Bill. The Environment Agency will take responsibility for the most difficult, 'special' sites and issue guidance to Local Authorities. The new legislation is likely to give an additional impetus to remediation.

LEARNING CURVE

The current state of knowledge of the extent of contaminated land in the UK is summarised above. The techniques for cleaning up groundwater affected by contaminated land depend on the contaminant and the hydrogeological setting. The many techniques are summarised in the paper on "Remediation" in this report. The US and Dutch experience suggests that clean-up of groundwater is very expensive and that in most cases restoring groundwater quality to drinking water standards is either completely impossible or not achievable within a reasonable cost and timescale. An increasing body of evidence shows that in the correct situations of hydraulics and geology, natural or intrinsic bioattenuation of many organics will occur given sufficiently long timescales. Experience of remediation of groundwater beneath and close to contaminated sites in the UK is limited, and little of the experience gained is shared within the scientific, industrial and regulatory communities. Remediation may be particularly difficult in the dual porosity aquifers of the UK, as pollutants which have diffused into the matrix may take a long time to diffuse back into the major water-bearing fissures. However, this is an important research area if the available options are to be evaluated effectively.

PERSPECTIVES

The government has conducted a review of the arrangements for dealing with contaminated land, and the DoE Framework for Contaminated Land together with the Environment Bill is the outcome. The onus is on developers to deal with the problem where sites change ownership or change uses but Local Authorities and the Environmental Agency will have powers to initiate clean-up in other situations where there are demonstrable risks to the environment or health.

Although the Environment Bill gives better guidance, liability for pollution of groundwater originating from contaminated land will remain unclear until more cases have passed through the legal system. With its present funding arrangements, the NRA and River Purification Boards in Scotland do not have adequate financial resources for undertaking significant remediation works and, in any case, have to seek DoE approval for major expenditures of this type. In any scenario, funding is likely to be a major constraint. It will be important to establish priorities and criteria for dealing with groundwater pollution caused by contaminated land, particularly from 'orphan sites' where the owner or polluter cannot be found or has insufficient resources to carry out remediation.

It would, however, be wrong to dismiss the potential for clean-up on the basis of costly experience in the US. Cost-benefit issues will be important. For example, the treatment of relatively low volumes of polluted water, at moderate to high concentrations paid for by the polluter or developer, compared with the cost of treating large volumes at low concentrations paid for by customers. However, cost-benefit studies can only be undertaken where information on the costs of clean-up and the standards to be met is available.

A major issue when dealing with contaminated land or groundwater remediation is to what level should clean-up take place. Because of groundwater's primary use as a source of drinking water, maximum levels demanded by drinking water Regulations are often used. However, these are often inappropriate where the aquifer is not a source of potable water or where natural attenuation processes are taking place. It is therefore difficult to set targets both for residual contamination in soils to limit continue leaching and for the groundwater itself. Methodologies are under development but this is an area where R & D can help to refine techniques for setting standards and thereby lead to more realistic and cost-effective remediation schemes.

BENEFITS AND BENEFICIARIES

The most immediate beneficiaries of remediation of contaminated land are the owners and/or occupiers of the re-developed land. In relation to groundwater, the beneficiaries are groundwater users, either those who draw groundwater for public or private supply from underlying aquifers, or the users of surface waters, estuaries or coastal waters to which groundwater flow is contributing. Research into remediation methods benefits the water industry, site owners, the NRA and River Purification Boards and the environment in general in providing more cost-effective ways of dealing with the problem of contaminated land.

RESPONSE

Aspinwall and Company have recently produced a report for the Department of the Environment giving a framework for assessing the impact of contaminated land on groundwater and surface water (Department of the Environment, 1994). This deals with the information needed to assess risks, procedures for categorizing and assessing risks and an evaluation of remedial methods. The British Standards Institute (1989) is currently in the process of drafting a code of practice for the identification of contaminated land.

The EC does not currently have a policy directly on the problem of contaminated land, but it appears that steps may be taken to establish such a policy. All EC legislation in the environmental sphere is governed by the precautionary principle, preventive action and the "polluter pays" principle. The existing Directive 80/68/EEC dealing with groundwater protection is intended to prevent pollution of groundwater by discharges of substances on Lists I and II of that Directive. This is to be achieved by preventing discharges of these substances directly to groundwater and regulating and controlling operations which might result in them entering groundwater after percolation through the soil.

More recently, two draft directives are being prepared which have an important bearing on the issue of contaminated land. These are the draft Landfill Directive (COM[91]Final), which aims to harmonise technical and environmental standards related to landfills to protect the environment generally and soil and groundwater particularly. A standardised methodology for investigating contaminated land would be highly desirable, and must be the ultimate goal. As a significant proportion of the contaminated sites which can give rise to groundwater quality problems are landfills, this Directive will be of great importance in defining the UK response to contaminated land. Secondly, a Draft Directive on Civil Liability in Waste (COM[91]219) would impose civil liability irrespective of fault on the producers of waste which cause damage to persons or the environment. However, there are important implications of such an approach regarding insurance cover for industry, and there has been no progress on this directive for several years. More recently still, the EC has produced a Green Paper on Remedying Environmental Damage which may replace the earlier draft directive.

The DoE has an active research programme on contaminated land and is issuing guidance on site investigation, clean-up and sampling etc based on this (Department of the Environment, 1994). The NRA also has a smaller programme and have issued guidance on leaching tests. The two programmes will merge under the Environment Agency in 1996. With the higher profile that contaminated land will have under the new legislation introduced in the Environment Bill, many of the issues relating to clean-up standards, their achievability and the cost-benefit of so doing will require a focused and coordinated research programme to underpin decision making by the Regulators.

R & D

- survey the extent of groundwater pollution from contaminated land
- monitor the effectiveness of clean-up procedures and review procedures for defining appropriate target clean-up levels
- determine the factors controlling the migration of contaminants through soil cover
- develop models and associated databases for pollutant transport through the saturated zones of UK aquifer and validate with appropriate experimental column studies
- determine *in situ* rates of biodegradation
- evaluate threat of remobilization of historic contamination
- develop and test reactive transport models
- determine extent of recharge and runoff and their influence on the threat to groundwater
- develop standard leachate tests & soil gas survey methodology for characterizing soil and aquifer contamination
- establish a 'flagship' site to implement an applied research programme.

REFERENCES

British Standards Institute (1989). BSI, Draft for Development 175. *Code of Practice for the Identification of Potentially Contaminated Land and its Investigation.*

Department of the Environment (1994). A Framework for Assessing the Impact of Contaminated Land on Groundwater and Surface Water. *Contaminated Land Research Report* (CLR) No 1 (2 volumes) prepared by Aspinwall and Company. London: Department of the Environment.

Harris, R. C. and G. Gates (1993). Contaminated land: Developments in NRA Policy and Practice. *Environmental Policy and Practice* 3: (2).

Harris, R. C. and R. J. Flavin (1991). Contaminated land: implications for water pollution. *J. Inst. Wat. Env. Man.* 5: 529-533.

House of Commons (1989). Environment Committee Report "*Contaminated Land*". London: HMSO.

National Rivers Authority (1994). *Contaminated land and the water environment*. Water Quality Series No 15. London: HMSO.

Visser, W. J. F. (1993). *Contaminated land policies in some industrialized countries*. The Hague: Technical Soil Protection Committee.

Authors: P J Chilton, BGS
R C Harris, NRA
G M Williams, BGS

Reviewers: S S D Foster, BGS
I H MacDonald, DoE
C Moss, Shropshire County Council
B Thomas, Thames Water Utilities Ltd

LANDFILL

PROBLEM STATUS

Approximately 70% of all controlled waste is landfilled because it is the cheapest method of waste disposal. Waste from mines and quarries, however, falls outside of current controls. Landfills produce leachates which can be grossly polluting if allowed to enter ground or surface water, so modern landfills are usually contained by engineered liners, and leachate within them controlled by pumping. Leachates may be treated on site (usually by aeration), pumped or tankered to sewer, and their production is minimised by completing the landfill with a low permeability domed cap.

There are, however, thousands of landfill sites in the UK. Many are old and disused and fall into the category of contaminated land. Little is known about their composition or hydrogeological situation and therefore their polluting potential. The pollution risk was not taken into account in choosing landfill sites and little effort was made to prevent pollution nor to monitor the groundwater around them.

Modern landfills have to be large to be economically viable. There are no legal requirements governing the types of liner that can be used and the permeability of the underlying clay material, but there is better technical guidance available than in the past. Monitoring of liner performance and of groundwater is generally poor (Crofts and Campbell, 1990), and site investigation and performance prediction is not carried out to well-defined standards. Because of the "engineering" of the landfill, there has been a tendency to neglect the properties of the underlying strata and their ability to attenuate leachate migration. However, this view is changing as the philosophy of landfill design is reviewed.

While landfills have a high potential to pollute groundwater, this pollution, if it occurs, will be localised and therefore does not present as serious a problem to groundwater resources in general as the diffuse pollution from agricultural and industrial sources.

RELATED ISSUES

Contaminated land
Heavy metals
Subsurface methane

TRENDS

DOE is currently reviewing its national strategy on waste management (Department of Environment, 1994a,b). There will be a trend towards waste minimisation at source, more recycling, and an expansion of incineration and composting (aerobic/anaerobic). Inevitably the residues of these processes will need to be landfilled and their environmental fate in a variety of landfill

management scenarios will need to be assessed.
The proposed EC landfill Directive is likely to direct that co-disposal of industrial waste with domestic waste should be phased out and that specific waste streams should go to monofills. Problems with monofills will then be specific to the waste form and site characteristics and their performance and impacts should be easier to predict.

Landfill design has moved from the pre-1978 concepts of 'dilute and disperse' through 'dilute and attenuate' to partial and then full containment as at present. However, in terms of landfill engineering the use of flexible membrane liners and mineral liners is now being seen not as the only barrier to leachate escape but as one of a number of barriers of which natural geological containment is important. This arises from the acceptance that the man-made liner will fail at some time in the future and that some leakage is inevitable and manageable. The idea that a landfill should be designed such that when the liner fails the waste will have degraded and the leachate will be weak and have little polluting potential is gaining support. More emphasis will need to be put on achieving stabilisation of the waste in reasonable times and this will to an extent overlap into the area of anaerobic composting. The current practice of high density compaction of wastes which effectively reduces waste contact with water and its rate of degradation will need to be reconsidered. The development of highly efficient bioreactor landfills with high leaching rates and accelerated decomposition is one option that is being considered (Harris *et al.*, 1994; National Rivers Authority, 1995).

The Groundwater Protection Policy directs potentially polluting activities, such as landfill, away from areas of greatest vulnerability and so the siting of new landfill sites will be closely scrutinised. Raised landfills are a possibility (Harris, 1992; National Rivers Authority, 1995).

CONTEXT CHANGES

Many trends which occur in N America eventually translate to UK. Methane utilisation, and lining landfills are examples. With the need to get certificates of completion to relinquish responsibility for landfills, monitoring and modelling activities will assume new significance. The EC groundwater and landfill directives will continue to support the trend to containment sites. Installations must be designed and constructed to the highest standards with an emphasis on engineered containment providing long-term environmental protection. Following the US lead, Construction Quality Assurance (CQA) is becoming common practice and is, for example, now part of the consent procedure in Northern Ireland.

Following the passing for England and Wales of the Environmental Protection Act in 1990, new Waste Management Licensing Regulations came into force in May 1994. These replace the relevant sections of Part I of the 1974 Control of Pollution Act and hence represent the most radical change in UK waste regulation since the first control system was instituted in 1976. The new provisions also implement the requirements of EC Directive 75/442 on Waste as amended by Directive 91/156. They also seek to implement provisions of the Groundwater Directive by requiring applicants of waste management licences to include a hydrogeological study and risk assessment where a site may impact on the local groundwater. It is necessary to demonstrate that the groundwater will not be significantly polluted by List I or List II substances. Waste Regulatory Authorities are also required to review all existing licences which have groundwater implications.

LEARNING CURVE

Much is known about processes that occur in landfills but long term monitoring data to help predict future performance are scarce. Long term containment of wastes has not yet been demonstrated and remains uncertain so assessment of overall risk is poor.

Monitoring techniques could be improved (especially with modern geophysical techniques) and performance assessment of landfills is crude. Modelling complex chemical-microbial processes is still a long way off. Landfill site investigation is still variable in quality, and there are no well defined performance standards.

PERSPECTIVES

Landfill remains an important source of potential and actual groundwater pollution and is one of the principal categories of contaminated land. Extensive monitoring of groundwater quality around landfills is performed by operators, by the Waste Regulatory Authorities and by the NRA. There is, however, great scope for improving the technical aspects of the construction, siting and sampling of observation boreholes and in the interpretation of the results of such monitoring. The timescale over which a landfill should reach its final form is currently under discussion. Some believe that for landfills to be sustainable, they should reach their final, stable and unpolluting form within a generation, ie within about 30 years (Harris *et al.*, 1994). This would require irrigation as well as leachate collection and treatment.

BENEFITS AND BENEFICIARIES

Reducing the potential for landfills to affect groundwater quality both in the short and long term is of considerable economic benefit. It is better to prevent pollution, because to treat it after it has occurred is often not possible or may be extremely expensive. Many sections of the community benefit. The waste operators reduce their financial liability. The water regulations safeguard groundwater and surface water resources. Local communities benefit in terms of better health and environment.

RESPONSE

The DoE is actively seeking to put landfills on a more sustainable basis within the general framework of the polluter pays principle. A landfill tax has been proposed by the Government and this will have a major impact on the economics of landfilling. Details are still under discussion - the DoE have produced consultation papers on both the Landfill Tax and the future Waste Strategy. As far as landfill leakage is concerned, the emphasis will be on ensuring that any leakage is at an acceptable level and that there is a minimum level of monitoring in place. The revision of Waste Management Paper (WMP) 4 has put into place statutory monitoring requirements and the revision of WMP 26 (Department of the Environment, 1995) includes specific guidance on the monitoring of landfills. Special arrangements will also be put in place for monitoring and controlling any closed landfill sites which come within the definition of contaminated land.

A national GIS for landfills is in the process of development for the DoE and data on the risks posed by each landfill in the UK are currently being gathered.

R & D

- review current monitoring data to identify the extent of groundwater contamination by landfill
- source identification of gases, gas generation and transport
- evaluate leachate transport and attenuation and degradation in UK aquifers
- quantify biogeochemical processes in aquifers and the influence of a cocktail of contaminants
- determine the importance of preferential flow in relation to the contamination of minor aquifers by landfills (especially in Scotland)
- develop techniques and/or instrumentation for: the early detection of leaks, remote leachate monitoring and for effective drainage blankets
- establish a 'flagship' site to implement an applied research programme.

REFERENCES

Crofts, B. and D. J. V. Campbell (1990). Characterisation of 100 UK landfill sites. In *'Harwell Waste Management Symposium'*, 1990.

Department of the Environment (1994a). Waste Management Papers Nos. 4 and 26A. London: HMSO.

Department of the Environment (1994b). Landfill Co-disposal. Waste Management Paper 26F. London: HMSO.

Department of the Environment (1995). Landfill Operation. Waste Management Paper 26B. London: HMSO.

Harris, R. C. (1992). Strategic planning for new waste disposal sites and groundwater protection policy. *Waste Planning* **2**: 3-6.

Harris, R. C., K. Knox and N. Walker (1994). A strategy for the development of sustainable landfill design and operation. *Waste Management Proceedings* (January 1994), p. 26-29.

National Rivers Authority (1995). Landfill and the Water Environment: NRA Position Paper. Bristol: National Rivers Authority.

Authors: P J Chilton, BGS
R C Harris, NRA
G M Williams, BGS

Reviewers: S S D Foster, BGS
A S Bradley, CBI
I H MacDonald, DoE

LAND-USE CHANGE

PROBLEM STATUS

The total land area of the UK is 240,000 km^2, approximately 70% of which is farmland, 10% is forest, and a further 10% is wetlands and semi-natural habitats. The remaining 10% is mainly urban land but also includes major transport routes, mineral workings and derelict land (Department of the Environment, 1992). Since most of the UK's major aquifers underlie good agricultural land, the effects of land-use change will largely reflect changes in the farming systems practised.

Large-scale changes in land use occur slowly and often imperceptibly. In the long term, changes in land use can significantly affect the amount of groundwater recharge and its quality. In the past, this was often not considered explicitly in the planning process and land-use planners are still often ignorant of the impact that their decisions might have on groundwater.

The reasons why the impacts of land-use change are not fully considered in the planning process are: the long delay often found between changes at the surface and changes in groundwater; the lack of effective planning tools for predicting the effect of land-use changes on a catchment-wide basis, and the difference in disciplines between planners (in the broadest senses) and hydrogeologists. Nevertheless, the impacts can be highly significant. For example, part of the nitrate load now reaching groundwaters has been attributed to the increased mineralization of nitrogen following the ploughing up of permanent grassland after the Second World War. More recently, the various changes in cropping patterns (winter vs spring sown cereals), pesticide usage and land use (set-aside, National Forests, ESAs) can all be expected to be reflected in future changes in groundwater quality. The introduction of specific groundwater protection measures (NSAs, NVZs etc) are clearly intended to benefit groundwater quality in the long-term. Therefore the control of the activities taking place on the land, both through statutory and non-statutory means, is now increasingly being seen as a key component of a long-term groundwater protection policy (Burt and Haycock, 1993).

Land-use changes can also affect the local demand for water including that of groundwater through the increased use of irrigation and the extension of industrial or urban areas. The expansion of towns in the upper parts of catchments can be particularly difficult.

The large scale conversion of upland grazing and moorland to conifer (mostly spruce) plantation is the major land-use change this century with 1/3 of all farmland lost going to forestry. Between 1947 and 1991, the total area of conifer forest increased from 0.38 million ha to 1.5 million ha (Department of the Environment, 1992). Since most of these changes took place in areas where major aquifers are absent, their impact on groundwater has been relatively small. This could change as new afforestation is increasingly being focused in the lowland areas.

There has also been a continuing loss of land to urban growth and road building and this impacts directly on groundwater recharge and quality. There are indications that the loss of agricultural land to urban development is slowing down with only 15,000 ha/a being lost over the last 5 years.

The inflexibility in many aspects of the planning system often makes it impossible to predict what future land-use changes may occur and what their impacts on groundwater might be. It is especially difficult to make predictions on a catchment-wide basis. There is also a common ignorance of land-use planners about the impact that their decisions might have on water. This is compounded by the lack of practical tools for transferring the results of research into output that can inform policy decisions.

RELATED ISSUES

Acid mine drainage
Afforestation
Contaminated land
Resource protection and vulnerability

TRENDS

In the short-term, the surplus food production within the European Union is likely to lead to increasing demands for a reduction in production. The present 'set-aside' policy is one of the means of achieving this. The set-aside requirement is under regular review - it has been agreed that the 1994/95 requirement for rotational set-aside in the UK has been reduced to 12% of the land cropped with cereals, oil seeds or protein crops and for 'flexible' set-aside from 18% to 15% of this land. The production of energy crops such as short rotation coppice may increase.

Even when the immediate consequences of changes in land use are known in terms of the changes in evaporation and leaching, which can be estimated from vegetation-soil models, the timescale of the response in the underlying aquifers is by no means certain. This will depend on many hydrogeological factors such as the depth to water table, the extent of preferential flow, the matrix porosity, the rate of recharge and the dilution within the aquifer itself. In general, response times of the order of 5-10 years can be expected in the Lincolnshire Limestone, 10-20 years in the Sherwood (Triassic) Sandstone and 20-50 years in the Chalk.

Some of the expected consequences of land-use change are listed in Table 1.

Table 1. Some possible consequences of changes in land use on groundwater.

Land use change	Consequences for groundwater
Increased set-aside land	Less pesticide leaching. Nitrate leaching probably reduced but may be increased if extensive rotational set aside. If some land is farmed more intensively, this could impact adversely on groundwater quality locally.
Arable land converted to forest	Expect decreased pollution from pesticides & nitrate but must be careful to prevent excessive nitrate leaching in mature forest and when timber harvested. Short rotation coppice & especially conifers may reduce recharge.
Increased outside pig production	Can lead to excessive nitrate leaching.
Increased/ decreased irrigation	Increases demand for water especially during dry summers. Irrigation tends to be favoured on lighter soils and may result in increased drainage. The more intensive production practised on irrigated land can lead to an increased risk of groundwater pollution.
Organic farming	Pesticide leaching down but nitrate leaching may be up.
Urbanization	Leads to increased likelihood of groundwater pollution from diverse industrial and domestic sources.
Ploughing up of old grassland	Leads to increased nitrate leaching due to mineralization of soil organic matter.
Environmentally sensitive management practices	The introduction of ESA's, NSA's, NVZ,s etc. should lead to improved groundwater quality, preservation of wetlands etc.

CONTEXT CHANGES

After a period of sustained growth in global grain production brought about by new plant varieties and the increased use of fertilizers, pesticides and irrigation (the 'green revolution'), the global per capita grain production has peaked and is likely to fall in the future. On a global basis, most of the land that can be readily cultivated already is. Therefore the present surplus food production within the EU must be set against a picture of increasing global food shortages.

There is pressure to reduce the extent of agricultural subsidies and in the short-term at least, there is likely to be diversification in the use of the countryside away from farming to more recreational use, food processing and retailing etc.

In recent years, afforestation, which can have quite large and long-term consequences on groundwater recharge and water quality, has changed emphasis away from upland, coniferous plantations towards smaller, multipurpose broadleaf plantations in the lowlands.

There may be important changes in farming brought about by changes in public attitude to animal welfare and other environmental issues. These might impact on groundwater. The increase in pig rearing outside, especially on some of the well-drained chalk soils, is a recent example which might locally lead to increased nitrate leaching (Worthington and Danks, 1994). Other examples might include an increase in organic farming and a reduction in pesticide use. There may also be an increase in protected areas such as Environmentally Sensitive Areas and Nitrate Sensitive Areas. The use of land close to borehole sources, is likely to be more sensitively managed under the guidance of the evolving Groundwater Protection Policy. However, response times between land-use changes and perceptible changes in the quality of pumped groundwater can be decades (Chilton and Foster, 1991).

LEARNING CURVE

Land-use changes can have a wide range of hydrological effects (Whitby, 1992; Calder, 1993). There are so many possible combinations of vegetation, soil, aquifer and climate that the influence of land-use change on groundwater quantity and quality can only be predicted using integrated models that consider all of the principal processes involved. Such models benefit from advances in many areas of science and although a number of such models already exist, many details remain uncertain, eg groundwater flow in both the unsaturated and saturated zones, and quantifying the rate of chemical processes in the subsurface. Solute transport (water quality) models are much more demanding of calibration data (observations) than strictly flow models.

A recurring problem in the application of such models is how to estimate hydraulic and other parameters which are usually measured on a point scale but which need to be known for an entire grid square (in the modelling sense) -

typically a 200 m x 200 m area. This is known as the 'upscaling' problem.

The application of modern technology (remote sensing, GIS etc) has made an important contribution to the rapid collection and display of land-use data on a national scale.

PERSPECTIVES

Many government departments, industries, organizations and individuals have an interest in land-use change, often from differing perspectives. Although groundwater protection is but one of these perspectives, it has achieved greater prominence in recent years (low flows, nitrate leaching, wetlands, etc).

BENEFITS AND BENEFICIARIES

Land-use changes on a large scale can have far reaching effects on water resources both for the better and for the worse depending on the change. Research in this area aims to anticipate the effect of such changes usually through some form of modelling - the changes themselves may take years to show in the groundwater.

Land-use changes impact on the policies of many government departments, directly or indirectly. Those interested in water-related issues most closely are likely to be the DoE and MAFF as well as statutory bodies such as the NRA. Many other interested parties such as the Countryside Commission, CPRE, NFU, Forestry Authority and English Nature might also be involved. The Water Utilities would also be concerned with any changes to their catchments that might significantly affect water yield, or water quality.

RESPONSE

Significant changes in land use are usually subject to an extensive planning process in which the impact on groundwater is now often seen as an important issue. Access to information on land use has improved greatly in recent years. The DoE commissioned the Institute of Terrestrial Ecology to produce the Countryside Information System (CIS), a computerised system for policy advisors, planners and researchers which includes land-use data for Great Britain at a 1 km square resolution. The CIS includes information from earlier surveys. It also includes data on geology, soils and freshwater invertebrate communities. Land cover change (1984-1990) is specifically covered.

The NERC has identified land-use change as an important issue for the future. A NERC programme called Land Use Foresight Exercise (LURFEX) was recently begun which aims to assess and identify key land-use issues over the next 10-20 years. There is also a NERC/ESRC Land Use Programme (NELUP) at the University of Newcastle.

R & D

- improve models for estimating the effect of land-use change on groundwater recharge and water quality and link these models to existing land use and hydrological databases so that they can become effective tools for land-use planners
- evaluate the consequences of the spread of the 'built' environment on groundwater resources and quality
- improve digital databases for critical hydrogeological and hydrogeochemical parameters of different aquifers
- improve coupled, surface water and groundwater models.

REFERENCES

Burt, T. P. and N. E. Haycock (1993). Controlling losses of nitrate by changing land use. In '*Nitrate: Processes, Patterns and Management*', eds. T.P. Burt, A.L. Heathwaite and S.T. Trudgill, pp. 341-367. Chichester: Wiley.

Calder, I.R. (1993). Hydrologic effects of land use change. In '*Handbook of Hydrology*', ed. D. R. Maidment, Chapter 13, pp. 13.1-13.50. New York: McGraw-Hill.

Chilton, P. J. and S. S. D. Foster (1991). Control of ground-water nitrate pollution in Britain by land-use change. In '*Nitrate Contamination*', ed. I. Bogardi and R. D. Kuzelka, NATO ASI Series, Vol. G30. pp. 333-347. Berlin: Springer-Verlag.

Department of the Environment (1992). *The UK Environment*. London: HMSO.

Whitby, M. C. (ed.) (1992). *Land use change: the causes and consequences*. ITE Symposium No. 27. London: HMSO.

Worthington, T. R. and P. W. Danks (1994). Nitrate leaching and intensive outdoor pig production. *Soil Use and Management* **10**: ii.

Author: D G Kinniburgh, BGS

Reviewers: I N Gale, BGS
A C Skinner, NRA
A R Agg, FWR

LOW FLOWS

PROBLEM STATUS

In this context the 'low flows' issue refers to the reduction of river flows due to a reduced groundwater contribution. The low flow regime of a river controls a wide range of natural and water resource development issues. These include the diversity and biomass of instream fish, invertebrates and macrophytes and a wide range of fauna and flora associated with the river corridor. In the context of industrial, agricultural and domestic water resources, low flows are critical for maintaining surface water abstractions (both direct and those controlled by reservoir storage), dilution of effluents, navigation and hydropower. Furthermore low discharges influence the perceived value of a river for general recreation and amenity value.

Both natural and water resource issues on a river system are controlled by the variability of river flows. The primary problem arises if this variability is changed, particularly with respect to a reduction in low flows. This may impose stress either on the natural ecological system or the availability of the water resource to meet demands made on the river. Key problems are caused primarily by climatic variability, change in land use (urbanisation, afforestation, agriculture), changes in groundwater pumping or surface water abstraction, effluent discharges and reservoir storage. All of these influences which affect water quantity will have an impact on water quality. A fundamental strategic issue is to develop methods for allocating resources between the abstractor, effluent discharger and the environment/recreational user.

Many river basins formally or incidentally operate conjunctive use schemes where the needs of abstractors are met from both groundwater and surface water sources. A significant factor in the conjunctive use of groundwater, river (direct and regulated) and direct storage water supply systems is the rate of response of the groundwater system to abstraction and the consequent effect on the contribution to river flows from groundwater. Other significant factors include, customer reaction/complaints following frequent or regular switching of waters of very different qualities (hardness etc) and the cost of providing duplicated provision of abstraction/treatment capacity. In south east England, for reasons of land-take or geological unsuitability, reservoir construction, considered by some, to be undesirable, and topography may not favour bulk transfers. Studies into conjunctive use of rivers and groundwater, involving the potential for artificial recharge of groundwater, may provide the solution by balancing local resources to meet demand.

RELATED ISSUES

Sustainable yield
Wetland conservation

TRENDS

There is no firm evidence that there are significant trends in the natural variability of low flows. However, there have been a number of significant drought years in the last twenty years; most notable in terms of intensity and spatial extent have been the 1975/6 and 1989-92 droughts. The latter was notable for the reduction in the length of river network in headwater streams and this was accentuated in areas of southern and eastern Britain where groundwater abstractions resulted in severe depletion of low flows. Although attention has focused on problem rivers, as identified by the National Rivers Authority (NRA, 1993a), there are some rivers which have had a significant increase in low flows above the natural regime, either as a result of augmentation from groundwater or surface water storage (compensation releases) or from an increase in industrial or domestic effluents. However, with the increased utilization of groundwater resources (particularly in the southern and eastern areas of Britain) and the associated impact on low river flows, many rivers are reaching the limit of their resources allocatable to abstraction and some have passed it. With the objective of utilising available water resources more effectively prescribed flow controls are increasingly being used to limit abstractions during periods of low flow. In many parts of southern England new agricultural licences are required to abstract in winter to storage.

CONTEXT CHANGES

The primary changes will result from increased water resource demand from domestic or agricultural sectors. In the case of the former it is anticipated that this will be moderated for some years as a result of reduction in supply leakage, introduction of metering and possibly by further improvements in the management of water resource systems although the water companies contend that maintenance of current leakage levels economically unsustainable and that water metering is both expensive and unproven as a long term suppressor of demand. Changes in irrigation demand will be influenced by EC agricultural policy, by commodity prices and by the frequency of natural droughts, particularly those in spring and early summer, not necessarily of an extreme return period. A change in the perceived balance between the abstraction and the environmental demands could also influence the significance of specific low flow problems. The influence of climate variability and the possible change in the frequency of extreme events could be critical, particularly in southern and eastern England where there is a fine balance between available resources and demand.

Institutional change, for example the establishment of both the UK and EU Environment Agency may also influence environmental policy in the area of low flow problems.

LEARNING CURVE

The key processes are well known in most aspects of low flow problems. These include an understanding of the spatial and seasonal variability of natural low flows and the significant artificial impacts which influence them. Statistical models have been developed to provide methods for predicting the magnitude, frequency and seasonality of low flows at gauged and ungauged sites. These methods are now being implemented in the UK water industry through the Institute of Hydrology's Micro LOW FLOWS software system, to provide a suite of consistent design techniques. There have been several studies where integrated surface water - groundwater models have been successfully applied to the investigation of low flow problems. However, there are a number of weaknesses in modelling the hydrological processes controlling leakage across river beds, resulting in difficulties in predicting the impact of change and particularly in the implementation and use of these models on a routine basis in the UK Water Industry.

Improving the water resources management of groundwater fed river basins, where there is appreciable abstraction from the groundwater, will require a much greater understanding of the temporal and spatial impacts of groundwater abstraction on low river flows. Models are extensively used by the UK water industry for assessing the interactions between aquifers and streams and the impact of groundwater abstraction on low flows. The National Rivers Authority (NRA) has statutory responsibility for river basin management issues in England and Wales, the River Purification Boards in Scotland and the Department of the Environment in Northern Ireland. From a review of existing regional NRA procedures (Bullock *et al.*, 1994) it was apparent that a number of different techniques are used for estimating the impact of groundwater pumping on low flows, including physically based modelling, analytical methods and rules of thumb.

Modelling solutions for predicting the impact of groundwater abstraction on stream flows fall into two groups; analytical models and numerical models. Analytical models have the advantage that, once the mathematics are understood, they are quick to apply and require a minimum amount of input data. The disadvantage is that solving the groundwater flow equations analytically requires a very idealised situation to be assumed and when the models are applied to real situations departures from this idealised situation result in poor estimation performance. Numerical models, on the other hand, when used to produce definitive catchment simulation are data hungry, require extensive calibration and thus tend to be very catchment specific. Numerical models have the advantage they are very flexible and can be used to model complex hydrogeological and hydrological configurations. However, it should be noted that the new generation of physically based models eg MIKESHE, do have user friendly interfaces to enable them to be used by water resources and water quality experts.

NRA staff have the task of assessing the impact of proposed groundwater licences on streamflow. The NRA have made extensive use of bespoke numerical models for groundwater resource assessment and impact on stream flow. Bespoke numerical models do not lend themselves to this task as they tend to be calibrated for specific catchments and tasks, and require specialist knowledge both to run them and interpret the output results. However, there is a large gap between these tools used to assess strategic resources issues and the operational requirements of the NRA licensing and consent staff.

Many groundwater fed streams have high amenity value. In recent years there is an increasing demand for water resources management practices to reflect the ecological needs of aquatic flora and fauna and the seasonality of those needs. Major advances have been made in relating low flows to habitat availability for aquatic flora and fauna through the use of the PHABSIM approach (NRA, 1993b). However, there is a long way to go before these very complex relationships are adequately understood.

PERSPECTIVES

The strategic issue for the UK Water Industry is to develop a balance between allocating water resources to meet the demands of an expanding economy demographic changes and increased concern for protecting the environment. This requires a legislative framework in which to operate, an understanding by the general public of these conflicting demands and of the costs of various options and the development of tools to balance these demands and the consistent implementation by the regulatory authorities.

BENEFITS AND BENEFICIARIES

The ultimate beneficiaries are the consumer: domestic, agricultural and industrial and the environment itself and the benefits to the public of enjoying the recreational and amenity aspects of sound environmental protection policies. These benefits would be achieved by providing improved management models to the water utilities, regulatory authorities and consultancy organisations.

RESPONSE

The current response by the regulatory authorities has been to develop strategies for the sustainable water resource development including models for predicting future demand and assessment of current and potential resources. R & D programmes have been initiated to develop management models for addressing some but not all low flow issues (NRA, 1993c) and improvement schemes are being implemented on a number of river systems. Past and ongoing research includes:

- Development of regional statistical methods for estimating natural low flows at ungauged sites from regional climatic databases and a classification of catchment hydrological response.
- Development of regionally applicable methods for estimating the impact of artificial influences on low flows, namely groundwater and surface water abstractions, discharges and impounding reservoirs.
- Development of a framework for an objective

method for the evaluation of prescribed minimum flows based on seasonal ecologically acceptable flows.

- Development of methods for sustainable groundwater resource assessment.
- Evaluation of the costs and benefits of low flow alleviation using environmental economics.
- The impact on water quality of crop water requirements, nutrient and pollution loads.
- Standardised assessments of low flow conditions.

R & D

- develop a consistent approach to coupling of operational hydrological models with time series and spatial databases in relation to impacts of low flows
- improve understanding of the relationship and nature of surface water-groundwater interactions, including improved understanding of valley bottom hydrogeology and impacts of groundwater abstraction
- use GIS to integrate soils, hydrogeology, land use, topography and climate data so as to improve low flow predictions
- improve low flow forecasting models
- improve understanding of the impact of changing low flows on freshwater ecology
- establish a 'flagship site' for low flows studies

REFERENCES

Gustard, A., A. Bullock and J. M. Dixon (1992). *Low Flow estimation in the United Kingdom.* IH Report No. 108. Wallingford: Institute of Hydrology.

NRA (1993a). *Low Flows and Water Resources. Facts on the top 40 low flow rivers in England and Wales.* National Rivers Authority.

NRA (1993b). *Ecologically Acceptable Flows: Assessment of Instream Flow Incremental Methodology.* NRA R&D Note 185. National Rivers Authority.

NRA (1993c). *NRA Water Resources Strategy.* National Rivers Authority.

NRA (1994). *Low Flow Estimation in Artificially Influenced Catchments.* NRA R&D Note 274. National Rivers Authority.

Authors: A Gustard, IH
A R Young, IH

Reviewers: I N Gale, BGS
R Gray, IWEM
K Martain, Thames Water Ltd

NITRATE

PROBLEM STATUS

Nitrate is a groundwater quality management issue in most European countries and in north America, and is beginning to appear as an issue elsewhere in the world as monitoring of water quality is developed. The documented causal link between high nitrate in drinking water and methaemoglobinaemia, and the possible link between nitrite and cancer have resulted in a relatively conservative approach to defining standards for nitrate in drinking water. Thus the EC Drinking Water Directive defines a maximum admissible concentration of 11.3 mg NO_3-N/l, a figure also adopted by the World Health Organisation as a guideline value. The US EPA has chosen 10 mg NO_3-N/l as its standard. Nitrate is also of concern as an important contributor to the eutrophication of inland and coastal waters.

Nitrate pollution of groundwater is difficult to control because the sources are diffuse and the pathways of deposition and transport and the processes of transformation are complex. Sources include intensive agricultural use of organic and inorganic nitrogen fertilisers, ploughing of grassland, disposal of wastes from intensive livestock production, urban and industrial wastewater and atmospheric deposition. Of these, it is the nitrate of agricultural origin which constitutes the principal groundwater quality issue in the UK. Nitrate leached from beneath arable land or intensively managed grassland is transported through the unsaturated zone with the infiltrating recharge to the underlying groundwater. Because this movement is slow, there is often a delay of 5 to 50 years before water leaving the soil zone reaches groundwater abstraction sources. The full impact of increased leaching of nitrate was not felt immediately in supply sources, and there is a corresponding time lag before the beneficial impacts of changes in agricultural practice are felt.

The extent of groundwater pollution by nitrate in the UK is well documented. The worst affected areas are the drier eastern and central parts of the country where the lower rainfall produces less infiltration to dilute nitrate concentrations. This reflects the increased leaching of nitrate below the soil resulting from expansion of the area under cultivation during and after the war and intensification of crop production by increased fertiliser use from the 1960s. The adoption of the EC Drinking Water Directive meant that many public supply sources were providing groundwater with concentrations exceeding or close to the maximum admissible concentration. It was estimated in 1989 that approximately one per cent of the population were receiving water which regularly failed to comply, and 3-4 per cent water which occasionally exceeded the maximum admissible concentration. The UK's approach to the problem has combined preventive measures to reduce nitrogen leaching and curative measures to reduce the nitrate concentration of water going into supply. For the water industry, the capital cost of compliance is high, and was estimated in 1989 to be about £90 million in six years and perhaps £200 million over the next two decades. Operating costs of nitrate treatment are also high, particularly where there is no convenient disposal route for waste products from the treatment process.

RELATED ISSUES

Afforestation
Land-use change
Resource protection and vulnerability
Source protection

TRENDS

Nitrate concentrations in groundwater have been rising steadily in many areas for 20-30 years, and continue to rise. In 1970, nitrate concentrations in some 60 public supply sources exceeded 11.3 mg NO_3-N/l at some time. This had risen to 90 in 1980, 105 in 1984 and 142 in 1987 (DoE, 1986; House of Lords, 1989), and 192 by 1990. In 1986, the Nitrate Coordination Group concluded that nitrate concentrations in groundwater would continue to increase in most unconfined aquifers, where natural denitrification processes are unlikely to be active (DoE, 1986). In low rainfall areas of eastern and southern England it was estimated that, with nitrogen inputs from agricultural land which were then current, nitrate concentrations in groundwater from many sources were thought likely to exceed 22.6 mg NO_3-N/l in the long term. Other sources were likely to reach equilibrium at concentrations between 11.3 and 22.6 mg NO_3-N/l. More recently, the large volume of water quality data presented in the annual reports of the Department of the Environment's Drinking Water Inspectorate (DWI) indicates that there is 3-4% non-compliance with the EC nitrate standard for drinking waters. However, DWI statistics are derived from 'water supply zones' after treatment and blending, and cannot be related easily to the actual quality of groundwater in aquifers.

Similar trends have been observed in surface waters in some parts of Scotland and it may be assumed that the trends are mirrored in groundwater. However, in Scotland only about 3% of all potable supplies are provided by groundwater, and groundwater has not received the same monitoring attention as in other parts of the UK. Nitrate is not a major problem in Northern Ireland.

CONTEXT CHANGES

Nitrate has been the focus of significant European legislation because elevated nitrate concentrations in the water environment may present problems both with respect to potability and eutrophication. The Drinking Water Directive (80/778/EEC) was implemented in 1985, and since then water undertakings have carried out costly programmes to enable them to comply. Measures undertaken include replacement of sources, blending and treatment. Where adequate resources of water with low to moderate nitrate concentrations exist to permit effective blending programmes, then the security of these lower-nitrate resources becomes an important issue for the water companies. This is a particularly important issue when designating Nitrate Vulnerable Zones. Sources which do not meet the DoE criteria for inclusion may nevertheless be critical to the success of large blending schemes.

In 1990, the Government established the Pilot Nitrate Sensitive Areas Scheme to test the effectiveness in practice of measures designed to reduce nitrate leaching. Ten pilot Nitrate Sensitive Areas (NSAs) were selected, representative of the range of farming practices, climatic conditions and hydrogeological situations. Each was defined as the catchment of a public supply source. Within the NSAs, farmers were encouraged to implement voluntary changes in agricultural practice, in return for agreed payments. An additional 22 Nitrate Sensitive Areas were designated in 1994, covering a further 28 sources. No NSAs have been established in Scotland.

More recently, the EC has implemented the Nitrate Directive (91/676). This requires member states to identify those areas of their territory in which the nitrate concentration of surface water or groundwater already exceeds 11.3 mg NO_3-N/l, or is likely to exceed this figure. These areas, known as Nitrate Vulnerable Zones (NVZs), are currently being designated; the consultation document envisaged a total of 72 such zones in England and Wales, both surface water and groundwater catchments, totalling about 650,000 ha. Two zones have been proposed for Scotland; a small area in Fife identified from groundwater nitrate concentrations and some 68,000 ha. Two zones have been proposed for Scotland; a small area in Fife identified from groundwater nitrate concentrations and some 68,000 ha embracing the whole of the River Ythan catchment because of the eutrophic conditions in the estuary. Member states are then required to develop action plans for controlling nitrate concentrations by the end of 1995, and to fully implement these plans by 1999.

LEARNING CURVE

Research into the occurrence and behaviour of nitrate in soils and groundwater has been extensive, both by the agricultural and environmental research communities. Initially, in the 1970s and earlier, efforts were concentrated on quantifying nitrate leaching losses. Lysimeters have been one of the most widely used approaches by agricultural researchers, and many of the long-established experiments at Rothamsted are based on them (Addiscott *et al.*, 1991). Porous cup suction samplers have also been widely used. Within the environmental community, investigations have included undisturbed sampling in the unsaturated and saturated zones of the major UK aquifers to observe vertical solute profiles and their evolution with time, under a wide range of land-use types (Foster *et al.*, 1986). As a result, a reasonably comprehensive picture of nitrate leaching losses has been obtained. There is general agreement that the nitrate lost from farming systems and hence the concentration of nitrate in groundwater beneath agricultural areas depends on the balance between inputs of nitrogen as organic and inorganic fertilisers and the quantity removed in crops and animal products. However, the behaviour of nitrogen in the soil is complex, and includes other processes such as ammonia and nitrous oxide emissions and incorporation into soil organic matter. Modelling techniques were developed to simulate nitrate leaching losses and compare these with field observations.

More recently, and in response to the developing legislative framework, research by the agricultural community has looked at ways in which nitrate leaching losses might be reduced. Approaches such as modifying tillage practices, modifying the timing and amounts of fertiliser and slurry applications, avoiding bare ground in autumn and winter by the use of catch crops and autumn sowing of cereals and changing land use have all been investigated (MAFF, 1993). Modelling studies have attempted to predict future nitrate concentrations if current land use continues, and for a variety of changing scenarios.

Much research effort has gone into understanding the processes of nitrogen cycling in agricultural soils (Addiscott *et al.*, 1991; Burt *et al.*, 1993). In terms of groundwater quality, it is mainly the nitrate produced by mineralisation which is available for leaching, although processes beneath the soil can still modify its transport to aquifers. Beneath the active soil layer, there remains the possibility of denitrification. Although there are much smaller microbial populations than in the soil and a restricted supply of nutrients, the potential for microbial denitrification has been demonstrated for each of the UK's major aquifers, by the isolation of suitable bacterial groups. Laboratory experiments have demonstrated their potential to denitrify, and the likelihood that denitrification occurs in confined aquifers has been demonstrated. However, the extent and rate of denitrification under natural conditions in unconfined aquifers and in the unsaturated zone remains unknown.

PERSPECTIVES

For many water utilities, the principal benefit from implementation of the Nitrate Directive would be that the land use controls introduced would reduce or eliminate the need for measures, additional to those already taken, to ensure compliance with the Drinking Water Directive. It is of concern to the industry that blending strategies already adopted will not, on their own, provide a permanent solution and that a reduction in nitrate leaching from the implementation of NVZs will come too late and be too little to avoid the need for very expensive treatment to remove nitrate.

Where nitrate concentrations are already high and nitrate removal plants have been installed, water utilities are also concerned to see measures in place which will help moderate rising trends, especially in fissured aquifers where response is rapid and extreme fluctuations make cost-effective operation of the treatment plant more difficult.

BENEFITS AND BENEFICIARIES

Understanding the extent and processes of nitrate pollution of groundwater helps the water industry, the NRA, DoE and MAFF to prepare programmes to control pollution in response to EC legislation. The initial work on the unsaturated zone demonstrated the time scale over which the deterioration in quality would continue, and indicated possible peak concentrations, if land-use practices at the time (late 1970s) continued unchanged. Subsequently, agronomic research has produced a range of approaches to modifying cultivation practices to assist in minimising nitrate leaching, and these have formed the basis of "Good Agricultural Practice". This research has also demonstrated the benefits of land-use change in reducing nitrate leaching where greater reductions in leaching than can be achieved by good agricultural practice alone are required.

The nitrate issue has also stimulated research on treatment processes for the removal of nitrate.

RESPONSE

The European legislative response to increasing nitrate concentrations in surface waters and groundwaters described above has been comprehensive. Initially, the UK's response to EC legislation was characterised by a reluctance to fully implement the Drinking Water Directive. Because of the high costs of compliance for the water industry, and because of the belief in the farming community that their livelihoods would be jeopardised if severe measures to control fertiliser use and disposal of animal wastes were introduced, the issue of nitrate in water became highly political. This manifested itself in a reluctance of vested interests on both sides to accept the maximum admissible concentration prescribed in the Directive. Thus, although passed in 1980, the Drinking Water Directive was not implemented in the UK until 1985, and only became transposed into UK law by the 1989 Water Quality Regulations.

Subsequently, the water industry has embarked on an accelerated programme of investment to achieve compliance, by blending water in supply from high and low nitrate sources, by installing treatment works to remove nitrate by developing replacement sources, and by improved sewage treatment to reduce the nitrate loading to surface waters. The target for compliance set by the UK Government is 1995.

R & D

- examine the processes of and quantify denitrification in aquifers
- analyse the effectiveness of artificial-recharge as a strategy for the treatment of high nitrate groundwater
- assess the importance of preferential flow in the transport of nitrate in both the unsaturated and saturated zones
- improve understanding of downward leaching of nitrate from particular soil/crops systems
- improve understanding of post-drought variations in nitrate concentrations
- characterize non-agricultural sources of nitrate in groundwater
- assess the effect of changes in agricultural practices using nitrate records.

REFERENCES

Addiscott, T. M., A. P. Whitmore and D. S. Powlson (1991). *Farming, Fertilisers and the Nitrate Problem.* Wallingford: C. A. B. International, pp 170.

Burt, T. P., A. L. Heathwaite and S. T. Trudgill (1993). *Nitrate: Processes, Patterns and Management*, pp 444. Chichester: J. Wiley & Sons.

DoE (1986). *Nitrate in Water.* Pollution Paper No 26. London: HMSO, pp 104.

Foster, S. S. D., L. R. Bridge, A. K. Geake, A. R. Lawrence and J. M. Parker (1986). *The Groundwater Nitrate Problem.* Hydrogeological Report 86/2. Keyworth: British Geological Survey.

House of Lords (1989). *Nitrate in Water.* Select Committee on the European Communities. London: HMSO, pp 274.

MAFF. (1993). *Solving the Nitrate Problem: Progress in Research and Development*, pp 37. London: MAFF.

Author: P J Chilton, BGS

Reviewers: D G Kinniburgh, BGS
S S D Foster, BGS
K Pugh, North East RPB
D Lyness, DoE (NI)
P Smyth, NFU
B Morris, NRA/BGS

NON-AQUEOUS PHASE LIQUIDS (NAPLs)

PROBLEM STATUS

Groundwater supplies face a threat from a wide range of synthetic organic chemicals. Some of these compounds have a low water solubility and, if spilled as concentrated liquids, may be present in the subsurface as non-aqueous phase liquids (NAPLS). Such spillages may occur as the result of leakages from underground tanks, accidental spillage or improper disposal. NAPLs can be broadly classified into liquids less dense than water (or light non-aqueous phase liquids (LNAPLs)) and denser than water liquids (DNAPLs). There are a large number of relatively water-insoluble organic compounds; the most commonly occurring LNAPLs include petroleum and diesel fuels, whilst halogenated solvents are the most frequently occurring DNAPLs. The permitted concentration of many of these compounds in drinking water is very low (in the ppb range) and, as these compounds are usually sufficiently water soluble to exceed these low limits, they pose a serious threat to the quality of groundwater to be used for potable supply.

NAPLs which are organohalogen compounds or mineral oils and hydrocarbons will usually be list I substances under the Groundwater Directive 80/68/EEC. These substances should be prevented from reaching groundwater.

Where NAPLs are present in an aquifer they represent a subsurface source of the pollutant; slow dissolution by flowing groundwater produces a plume of the aqueous phase contaminant which extends down groundwater gradient of the pollution source. Given the slow rates of dissolution in groundwater, such subsurface sources could persist for many years or even decades.

In general, the DNAPLs give rise to greater concern than the LNAPLs. This is because the latter float on groundwater and therefore are only present at relatively shallow depths (within the unsaturated zone and the zone of water table fluctuation). They are relatively easily contained by pumping; the LNAPL collects within the zone of water table depression. However, the movement of DNAPL in the subsurface is density driven and extremely complex; these liquids may penetrate the aquifer to considerable depth. The precise depth and rate of movement depends both on the characteristics of the aquifer and the properties of the liquid. In the case of the halogenated solvents, which have very low viscosities, rapid and deep penetration of fissured aquifers is anticipated. Pools of DNAPL may collect on less permeable horizons within or at the base of the aquifer. In addition during downward movement of DNAPL through the aquifer, some of the liquid will be retained within the rock matrix as a residual phase. The DNAPL pools and residuals will frequently form a larger component of the subsurface pollution than the aqueous, sorbed or gaseous phases.

Once an aquifer has become contaminated by DNAPL it is likely to remain so. The remedial measures currently available, such as pump and treat, are ineffective due to the slow dissolution of the non-aqueous phase and inaccessibility of the source to mobile groundwater with consequent slow migration to pumping sources.

RELATED ISSUES

Contaminated land
Remediation
Resource protection and vulnerability
Source protection

TRENDS

The usage of chlorinated solvents in the UK increased steadily from their introduction in the 1920s to peak levels in the mid 1970s. Since then, overall usage has declined by 20-40% partly due to changes in industrial type and to improvements in processes. Better housekeeping to meet current regulations should lead to fewer problems in the future.

Groundwater in urban areas has already shown widespread low-level contamination by organic compounds, much of which is historical. In addition, investigations of long-established industrial sites in urban areas, particularly for redevelopment, are likely to reveal serious contamination by a range of DNAPLs. It is also recognised that many airfields are underlain by an existing cocktail of NAPLs, both fuel and chlorinated solvents and investigations of petrol stations and large fuel users such as hauliers are likely to show widespread local contamination from fuel spillages and leaking tanks. However, many of the monitoring sites are pumped abstraction boreholes, which also draw in water from uncontaminated parts of the aquifer, and as a consequence introduce considerable dilution, making the scale of the problem unclear.

Whilst the number of new problems resulting from poor industrial handling practices will have been greatly reduced, a legacy of undiscovered contamination of the subsurface remains. Land-use changes resulting from urban and industrial redevelopment may lead to the mobilisation of these contaminants. The release of contaminants from NAPL retained in the unsaturated zone is also likely to occur if water levels are allowed to rise due to changes in abstraction patterns.

The introduction of unleaded petrol has resulted in increasing concentrations of the water-soluble and mobile additive methyl tertiary butyl ether (MTBE) being detected in groundwater.

CONTEXT CHANGES

The current water demand, particularly in southern

England, suggests that the loss of groundwater resources due to pollution cannot be afforded. Allowable concentrations in drinking water for the chlorinated solvents under EC Directives are already very low, ranging from 3 ppb for carbon tetrachloride to 30 ppb for trichloroethene. One serious spillage therefore has the potential to contaminate a very large volume of water to concentrations in excess of these limits.

Since the chlorinated solvents as well as CFCs are implicated in the depletion of the ozone layer, production of some compounds by the main manufacturer in the UK will be phased out under the Montreal Protocol.

LEARNING CURVE

The behaviour of LNAPLs is generally understood but it is not possible to predict the transport of DNAPL in other than a very generalised way. It is clear that NAPLs will act as a long term source of pollution in the aquifer, slowly dissolving in groundwater and producing a contaminant plume which may extend for a considerable distance down groundwater gradient.

There have been programmes of research into the occurrence and behaviour of chlorinated solvents in the major aquifers of the UK carried out by both BGS and Birmingham University. BGS studied incidents of groundwater pollution at several sites on the Chalk aquifer. Insight was gained into the mechanism of deep penetration of the aquifer by DNAPL. One of these sites subsequently became the subject of legal action by Cambridge Water against the Eastern Counties Leather Company.

Perhaps the single most difficult problem facing the hydrogeologist at sites where the aquifer has been (or is suspected of being) contaminated by DNAPL is to locate and quantify the subsurface DNAPL. In many cases, the presence of DNAPL can be surmised only by the presence of aqueous phase concentrations in excess of 1-10% of maximum solubility. Detailed investigations of contaminated sites including geophysical borehole logging, continuous porewater profiles and lithological description and aquifer characterisation using drilled core can provide further evidence of the presence of DNAPL. However at present, there is no existing technique able to quantify the volume of DNAPL present in the subsurface.

The key processes controlling the concentration of contaminant in the aquifer is the rate of dissolution from NAPL bodies. The geometry of these bodies in the sub-surface cannot be determined, particularly in fissured aquifers and it is therefore not possible to determine the rate of release.

PERSPECTIVES

Both light and dense NAPL's present problems for potable water supply in the UK; the former may be more common and widespread, the latter the more difficult and costly to remediate. While the legal liability situation remains unclear and until there is significant financial provision for taking remedial action in advance of what are likely to be lengthy legal proceedings to establish liability, remediation is likely to remain rarely undertaken. In the meantime, as in the case of other pollutants, the water industry is obliged to adopt post-pumping, pre-supply treatment or some replacement as its main approaches to compliance with drinking water standards for solvents.

BENEFITS AND BENEFICIARIES

Research on the detection, location and quantification of DNAPLs would benefit the design of aquifer clean-up schemes, enabling them to be both cheaper and more efficient. Primarily this would benefit those responsible for paying for clean-up, but it would also be of benefit to the Water Companies because in some instances it is cheaper in the longer term to clean up rather than to treat the supply. There is a need to develop cost effective actions to clean-up at source rather than allow the contamination of large volumes of groundwater. The NRA has published two reports which give its position in respect of pollution of water from land sources: Policy and Practice and Protection of Groundwater (1992) and contaminated land and the Water Environment (1994).

RESPONSE

The current response of the Water Companies is either to treat or close down contaminated supplies they may also blend with uncontaminated supplies. They try to seek compensation from the polluter. The NRA may attempt to identify the polluter where funds permit. It would often be more effective to contain and/or treat contaminated hot spots. Currently the NRA does not have the power to enhance this.

R & D

- carry out laboratory studies to investigate fundamental processes of DNAPL migration followed by verification at the field scale
- assess the importance of preferential flow
- develop practical use of multi-phase flow models (including the vapour phase) including parameter identification and aquifer characterization
- evaluate rapid methods for delineation of contaminated zones by surface geophysics and vapour surveys
- develop methods for the estimation of residual saturation in aquifers
- study interaction and passage of NAPLs through aquitards.

REFERENCES

Lawrence, A. R., M. E. Stuart, J. A. Barker, P. J.

Chilton, D. C. Gooddy and M. J. Bird (1992). Review of groundwater pollution of the Chalk aquifer by the halogenated solvents. *NRA R&D Note 46.*

Lawrence, A. R., J. A. Barker, M. J. Bird, D. C. Gooddy, R. J. Marks and M. E. Stuart (1992). Review of groundwater pollution of the Triassic Sandstone aquifer by the halogenated solvents. *NRA R&D Note 47.*

Lawrence, A. R. and S. S. D. Foster (1991). The legacy of aquifer pollution by industrial chemicals: technical appraisal and policy implications. *Quart. J. Eng. Geol.* **24**: 231-239.

Longstaff, S. L., P. J. Aldous, L. Clark, R. J. Flavin and J. Partington (1992). Contamination of the Chalk aquifer by chlorinated solvents: A case study of the Luton and Dunstable area. *J. Inst. Water Envir. Manag.* **6**: 541-550.

Rivett, M. O., D. N. Lerner and J. W. Lloyd (1990). Chlorinated solvents in UK aquifers. *J. Inst. Water Envir. Manag.* 4: 242-250.

Royal Commission on Environmental Pollution (1992). Groundwater, Chapter 5 in Sixteenth Report: Freshwater Quality, HMSO, London.

Authors: A R Lawrence, BGS
M E Stuart, BGS

Reviewers: P J Chilton, BGS
S S D Foster, BGS
A R Agg, FWR

PESTICIDES

PROBLEM STATUS

During the past 20 to 30 years, the use of specially-formulated pesticides has developed dramatically and globally the annual rate of increase in usage is now about 3-4%. Pesticide application has become an integral part of most crop production systems and a vast array of compounds is now available to farmers. In the United Kingdom, the most rapid growth has been associated with the increasing use of herbicides and fungicides in the cultivation of autumn-sown cereals, with lesser amounts used for fruit and vegetables. In the most recent years, with greater efficacy of new compounds, overall quantities applied are no longer increasing. Pesticides are increasingly designed for specific uses, and a wide range are in common agricultural use. Non-agricultural usage has been dominated by the use of triazine herbicides for general weed control of paved areas such as highways, airfields and car parks and of railway embankments, and forest firebreaks. Other compounds are used for pest control and preservation in agricultural- and forestry-based industries such as wood and textiles.

Techniques for the measurement of pesticide residues at low concentrations in the water environment are sophisticated and costly to perform. Routine monitoring of pesticides in groundwater has therefore lagged behind pesticide usage and has been carried out only since the late 1980s. As a consequence, the detection of pesticide residues in groundwater is relatively recent, and this has heightened public concern about their environmental behaviour.

The stringent maximum admissible concentration for pesticides in drinking water of 0.1 μg/l (in the EC Drinking Water Directive) has been exceeded in some public supplies in the UK, although concentrations above 1 μg/l have rarely been recorded. The water companies recorded 1,006,000 determinations of pesticides in 1993, of which about 2% exceeded 0.1 μg/l (DWI, 1994). Thirty four individual compounds were detected in 1993; the most frequently encountered to date all being herbicides derived from cereal cultivation and urban areas. The most affected areas are central, eastern and southern England as these are intensive arable areas and densely populated, and the regions of high usage of amenity herbicides. Those regions are also heavily dependent on groundwater. The persistent and widely used triazine amenity herbicides dominate the recorded exceedences to date, and water undertakings in these regions have faced major investments in treatment for pesticide removal to achieve compliance with the Directive.

RELATED ISSUES

Land-use change
Resource protection and vulnerability
Source protection

TRENDS

Reliable, confirmed detections of pesticides in groundwater have been available for too short a period for overall trends of pesticide occurrence in groundwater to be evaluated. At the present time, any apparent trends of increased number of positive determinations probably reflect increased sampling; the more one looks the more one finds. The first national picture of pesticide occurrence in groundwater was that published by Friends of the Earth (Lees and McVeigh, 1988). The most comprehensive current information comes from the annual reports of the Drinking Water Inspectorate, although this relates to water within the distribution system rather than raw water as it comes from the aquifer. Although the NRA carries out some pesticide analyses within its current monitoring programmes, it is as yet unable to provide a comprehensive national picture of pesticide occurrence in groundwater, from which trends be determined. The NRA is currently working to improve its groundwater quality monitoring activities, including pesticides, and from 1995 an improved quality archiving system will begin to incorporate pesticide data obtained both by the NRA and the water utilities. In addition, metabolites are excluded from current monitoring of pesticide concentrations in groundwater. There is even less information about pesticides in groundwater in Scotland and Northern Ireland.

CONTEXT CHANGES

Pesticide usage is complex and ever-changing. The most persistent and toxic organo-chlorine insecticides have been replaced by organo-phosphorus compounds and more recently by synthetic pyrethroids. The multinational pesticide companies are continually developing new compounds to provide the same benefits as existing pesticides, but at lower doses and with less potential for negative impacts on non-target organisms or on the environment. Thus although between 1980 and 1990 the total area of crops treated with pesticides in England and Wales increased by 10%, the total weight of pesticides applied has fallen by 20%.

The present maximum acceptable concentration in the EC Drinking Water Directive of 0.1 μg/l for any compound and 0.5 μg/l total pesticides was effectively a surrogate zero at the time the Directive was prepared. The Directive is currently under review; a new draft is likely to be produced by the end of 1994. There is some speculation about the approach that will be adopted, but it seems likely that the 0.5 μg/l total pesticides may fall away, since data purporting to meet this standard are meaningless as they include only the individual pesticides detected and take no account of the possible presence of undetermined compounds nor of metabolites.

The regular detection of the triazines and the 'substituted area' group of cereal herbicides in surface water and groundwater has resulted in review of approvals for use by the government's Advisory Committee on Pesticides. As a consequence, approval for the use of atrazine in non-agricultural situations was withdrawn in 1993. There has been a rapid reduction in atrazine concentrations in surface water in response, but not in groundwater. Many organisations replaced atrazine in their weed control programmes with compounds such as diuron and glyphosate, and the former is beginning to appear in public supply sources.

Increasing environmental awareness has resulted in improved guidance to farmers on the storage and use of pesticides, and the disposal of unwanted materials and effluents from washing or rinsing containers. Local, point-source pollution incidents from spillages or careless handling of pesticides should hopefully become less common as a result. There is a need for improved guidance on disposal in Codes of Practice, and disposal of residues and tank washings may in future require licensing to comply with the EC Framework Directive on Waste.

LEARNING CURVE

Research into pesticides in groundwater has been limited, partly because of the difficulties of representative sampling and relatively high analytical costs. The development of ELISA tests for pesticide detection may go some way towards easing the analytical burden, although some degree of confirmatory analysis by standard methods will always be required.

The fate and behaviour of pesticides in the environment are determined by a number of processes, principally: sorption, leaching, volatilisation, plant uptake, and degradation. The procedure by which a manufacturer registers a new compound for use includes laboratory and field studies (usually employing lysimeters) in "standard fertile, organic clay soils" to quantify these processes. Knowledge of fate and behaviour in soils is, therefore, extensive, although not comprehensive for the whole range of soil types, particularly the more permeable soils associated with the outcrops of the UK's major aquifers.

Relatively little is known about the behaviour of pesticides in the deeper subsurface. It can be anticipated that pesticide mobility will be greater in aquifers than in the soil because there is a much lower organic matter and clay content for adsorption. Attempts have been made to estimate mobility based on organic partition coefficients (Foster *et al.*, 1991). In addition the persistence of pesticide compounds may be many times greater in aquifers than in the soil. The unsaturated and saturated zones of aquifers have much less organic matter to provide substrate and nutrients, and a greatly reduced indigenous microbial population, than a typical agricultural soil. There are, however, as yet few estimates of the magnitude of this increase in persistence.

The hydrogeological characteristics of the main UK aquifers suggest a high probability of preferential flow in the unsaturated zone, by-passing the matrix of the aquifer (Foster *et al.*, 1991). Preferential flow is difficult to observe and quantify, especially under natural rainfall conditions and its role in the rapid transport of pesticides to the water table is not proven. Where developed, preferential flow could provide routes for compounds which are of low to moderate persistence to reach the water table even where the unsaturated zone is relatively thick, since there would be less opportunity for retardation by molecular diffusion into the matrix with associated adsorption and degradation reactions. Such rapid flow would be greatly favoured in situations where surface drainage was carried into the ground via soakaways. As these are often employed to drain railway embankments, highways, airports and other paved areas, they may be responsible for the widespread detection of triazines used as non-agricultural defoliants.

Both the British Geological Survey and WRc have carried out studies with NRA funding to determine the occurrence of pesticides in the unsaturated and saturated zones of the major UK aquifers. Both have detected very little pesticide residues in the matrix of the unsaturated zone beneath agricultural land, and generally low concentrations in groundwater. Atrazine was found more commonly and at higher concentrations than isoproturon, reflecting its greater persistence. Studies of pesticide residues in the runoff from individual rainfall events in small catchments indicate that much higher but transient concentrations can occur in surface waters.

In a joint study with the Institute of Hydrology, BGS is continuing to investigate the movement of pesticides in the unsaturated zone, to assess the frequency and magnitude of preferential flow events, and what antecedent soil moisture conditions are favourable for the initiation of preferential flow. The sampling of preferential flow in the unsaturated zone as it occurs remains an important technical constraint, and approaches are being developed to solve this problem. The other key issue is pesticide persistence in the unsaturated zone and this is also being addressed in the BGS/IH joint study and by other organisations.

PERSPECTIVES

For groundwater, the principal areas of interest are the present and future pesticide concentrations arising from current practices, the scope for protecting sources, and the likely scale of future costs resulting from changes in practices and/or products.

As in most groundwater quality issues, cost-benefit factors lie at the heart of the pesticides debate. Pesticide usage has increased because of the economic benefits which follow from effective pest control. However, when pesticide residues reach public water supply sources at concentrations which breach the EC Drinking Water Directive, there is a cost to the water industry and its customers of achieving compliance. This cost does not normally fall to the user who gained the benefit. One estimate puts the cost of compliance at around £870 million and, in a recent parliamentary reply, capital costs of pesticide treatment by water utilities in England and Wales were given as £122 million, £170 million and £207 million for 1992-93, 1993-94 and 1994-95 respectively.

Because of the high cost to the water industry of meeting the 0.1 μg/l standard, companies are interested in seeing pesticide contamination of groundwater minimized. As described below, approaches to this problem vary, some placing emphasis only on treatment while others are more interested in promoting practices which will help to reduce the potential for transport of pesticide residues to groundwater. Even in the former case, however, improved knowledge of pesticide behaviour is important for predicting maximum concentrations and duration of troublesome concentrations for designing and costing water treatment works.

BENEFITS AND BENEFICIARIES

The beneficiaries of research into the behaviour of pesticides in groundwater include the water industry and water consumers, the NRA, the farming community and other pesticide users, the Government and its pesticide approvals process and the manufacturers themselves. The water industry is interested in assessing the risk of pesticides used in the catchments of its sources finding their way into supply. Where this has already occurred, and treatment is required or may be required, then the likely peak concentrations and duration of pesticide occurrence are important design parameters.

Even where a pesticide, such as atrazine, is withdrawn for specific uses, knowledge of the compound's persistence in the subsurface is essential for estimating how long troublesome concentrations are likely to be maintained. When new pesticide compounds are brought in to replace withdrawn ones, knowledge of the behaviour of the newer compound is equally important. Sound knowledge of pesticide behaviour in the subsurface is also important to the manufacturers; it is much better to take precautionary measures related to pesticide usage based on sound scientific data rather than imposing draconian bans on usage because there is no data and in response to environmentalist pressures.

RESPONSE

One response to the stringent provisions in the EC Drinking Water Directive in relation to pesticides has been the rapid development of analytical techniques for pesticides in water. Detection limits for many compounds in water are now in the range of 0.01 μg/l. Other responses have included the development by the water industry (in the broadest sense) of treatment methods for the removal of pesticides, and treatment is now installed at a number of groundwater sources.

The regular detection of herbicide compounds in supply sources has led to the review of approvals for several compounds, as referred to above. The detection of atrazine from non-agricultural sources and concern about the likely transport to public supplies of the compounds which have replaced atrazine have led the water companies (particularly Severn-Trent Plc) to initiate publicity campaigns to encourage careful usage (SPRAYSAFE) and storage and disposal (CHEMSAFE) of pesticides, and in some cases to enter into specific local agreements to restrict pesticide usage in sensitive areas close to public supply sources (Thames Water Plc).

In addition, Severn-Trent Water has initiated catchment management plans, initially for surface water catchments to reservoirs but now being extended to groundwater source catchments. The latter is now more easily achieved following the definition of catchments and source protection zones by the NRA. A risk management tool aimed specifically at pesticides (CATCHIS, a CATCHment Information System) is being developed by SSLRC for Severn-Trent Water.

R & D

- determine rate of pesticide degradation in the unsaturated and saturated zones
- model pesticide transport from the soil zone
- study the behaviour of combinations of pesticides and the influence of DOC and nutrients
- study the effect and behaviour of formulation products and metabolites
- quantify the importance of preferential flow
- carry out a baseline survey of unsaturated zone pesticide profiles and observation boreholes
- improve analytical and assay techniques.

REFERENCES

Clark, L., J. Gomme, D. B. Oakes, S. Slade, M. Fielding, K. Moore, L. Taylor and S. Shurvell (1992). Pesticides in major aquifers, Phase I. *NRA R&D Note 72.*

Clark, L., J. Turrell, M. Fielding, D. B. Oakes, I. Wilson and L. Taylor (1994). Pesticides in major aquifers, Phase 2. *NRA R&D Project 439, Final Report.*

Chilton, P. J., M. E. Stuart, S. J. Gardner, C. D. Hughes, H. K. Jones, J. M. West, R. A. Nicholson, J. A. Barker, L. R. Bridge and D. C. Gooddy (1993). Diffuse pollution from land-use practices. *NRA Project Record 113/10/ST.*

Drinking Water Inspectorate (1994). *Annual Report for 1993.* London: Department of the Environment.

Foster, S. S. D., P. J. Chilton and M. E. Stuart (1991). Mechanisms of groundwater pollution by pesticides. *J. Inst. Water Env. Manag.* 5: 186-193.

Lees, A. and McVeigh, K (1988). *An Investigation of Pesticide Pollution in Drinking Water in England and Wales.* London: Friends of the Earth.

Authors: P J Chilton, BGS
M E Stuart, BGS

Reviewers: S S D Foster, BGS
D G Kinniburgh, BGS
P J Aldous, Thames Water Utilities
W A Virtue, Tweed RPB
P Smyth, NFU
D Lyness, DoE(NI)
R I Rodgers, Severn Trent Water Ltd
D Tester, NRA

REMEDIATION

PROBLEM STATUS

The wide range of synthetic organic compounds currently found in groundwater are often a legacy of previous industrial activity. These contaminants are quite frequently liquids and may have been derived from spillages, leakages, leaking tanks or improper disposal at the industrial site. The volumes of liquids that may have been released into the subsurface and the period of time over which such releases occurred are usually unknown. In addition, where these compounds have limited aqueous solubility they may be present in the subsurface as non-aqueous phase liquids (NAPLs). These liquids normally form persistent subsurface sources of contamination.

Aquifer remediation often focuses on containing and/or removing these liquid sources to prevent widespread contamination of the aquifer, since these liquids represent the single most important component (in terms of mass) of the contaminant in the aquifer. However, the determination of the quantity present and where it has accumulated presents considerable problems, particularly in the dual porosity aquifers of the UK.

The distribution of the contaminant, both within the aquifer and between different phases, must be determined. This is required firstly to allow the design of an efficient remediation strategy, and secondly to monitor the progress and effectiveness of the removal of the contaminant from the aquifer to determine the success of the clean-up. The contaminant may be present in both the saturated and unsaturated zones of the aquifer and occur as the mobile aqueous phase (in the matrix and fissure waters), as the sorbed phase and/or as NAPL. During remediation, transfer from one phase to another (eg NAPL to aqueous phase) nearly always takes place.

Methodologies for aquifer remediation fall into three types: (1) containment (eg pump and treat); (2) removal by volatilisation (eg gas purging of the volatile fraction), and (3) in-situ bioremediation. The remediation design needs to consider, amongst other factors, the contaminant distribution. This is the single most important factor, but can easily be overlooked.

Perhaps the most widely used method for aquifer remediation is to 'pump and treat'. This involves pumping groundwater from the contaminated aquifer, treating the water at the surface and reinjecting it into the aquifer up-gradient. This can both effectively contain and remove the contaminants. However unless designed to the contrary, groundwater is channelled through the more permeable horizons and these, as a consequence, are cleaned relatively easily and rapidly. Contaminants which may be present at much greater concentrations in the less permeable layers (eg the microporous matrix of the Chalk) may be practically unaffected by the circulating groundwater.

Similar problems of insufficient access to the contaminant, by circulating air in the case of volatile transfer or by microorganisms in bioremediation, due to a lack of knowledge of contaminant distribution, can lead to poor rates of contaminant removal and may necessitate lengthy and expensive remediation operations.

As remediation proceeds the progress of the clean-up has to be monitored. Pumped groundwater samples, which are often used to assess the effectiveness of the remediation, are unfortunately unreliable indicators. Such samples are representative of water quality in the more permeable horizons, not of the bulk of water stored in the aquifer. The concentration of the contaminant is likely to, and often does, show a rapid decline during early stages of remediation as the permeable layers are flushed. When pumping is stopped, contaminant concentrations in the permeable horizons increase as a result of diffusion and mixing with groundwater from the less permeable zones. In the case of the Chalk aquifer, the more permeable fissure component of groundwater represents only 1-2% of total rock volume, compared with 25-40% for relatively immobile porewater in the matrix. It is essential that the design and monitoring of remediation takes both the contaminant distribution and aquifer circulation into account.

RELATED ISSUES

Contaminated land
Heavy metals
Landfill

TRENDS

Redevelopment of former industrial sites is beginning to reveal serious groundwater contamination by a range of organic contaminants, including NAPLs. Aquifer remediation may be required at such sites.

In addition, investigations at and around oil fuel installations will certainly demonstrate the existence of light non-aqueous phase liquids (LNAPL) within the unsaturated zone and at the water table. Tertiary-butyl methyl ether (TBME) is a highly mobile and increasingly widespread groundwater contaminant derived from unleaded petrol. The presence of LNAPLs as sub-surface sources of TBME is a serious problem which cannot be ignored. Remediation of groundwater beneath oil fuel installations is becoming more widespread.

Aquifer remediation has been attempted at a number of sites where fuel oils and/or chlorinated solvents have been spilled. Few cases in the UK have been well documented and assessment of the success of remediation appears to be restricted to monitoring of pumped groundwater.

CONTEXT CHANGES

The current demand for water in south and south-east England suggests that the loss of groundwater resources due to pollution represents a serious potential threat to supplies. Remediation which attempts to reduce the spread of contamination through the aquifer is likely to be the most pragmatic response.

The Maastricht Treaty states that wherever possible pollution should be cleaned up at source. In the case of groundwater this would suggest that remediation of the aquifer close to the source of contamination is the preferred option, rather than the treatment of groundwater at the point of supply. European Community Law is likely to ensure that wherever possible aquifer remediation measures are enforced.

In Britain it is generally accepted that the 'polluter pays' principle should apply to groundwater contamination. This principle is ineffective in many cases due to the difficulties in both identifying the polluter and subsequently in proving liability, particularly in urban areas and where pollution is a legacy of past practices. The legal controversy over the incident of solvent pollution at Sawston, Cambridgeshire and the final decision against the Cambridge Water Company highlight the problems of recovering the costs from the polluter.

LEARNING CURVE

We are still at the bottom of the learning curve. Much of the albeit limited experience to date applies to the unconsolidated sedimentary aquifers of North America in which intergranular flow predominates. Dual-porosity aquifers add considerably to the complexity of the problem at all stages of remediation: investigation, implementation and monitoring. The scarcity of research into the processes controlling remediation and the lack of detailed monitoring at well documented sites considerably hinders our understanding.

Recent work by Parker *et al.* (1994) demonstrates the complexity of modelling immiscible phase behaviour in fractured aquifers. The rate of apparent disappearance of the NAPL by diffusion into the surrounding matrix porewaters is highly dependent on the geometry of the aquifer and will control the concentration seen in the pumped aqueous phase and the amount available for removal.

There are a few documented examples of remediation of the major UK aquifers. However all these cases appear to use the pumped water concentration as the only means of assessment of progress and no estimation of pollutant remaining in the aquifer matrix has been made.

Existing technologies may be able to reduce the risks posed by groundwater contamination, in particular by containment of the problem, but restoration of all contaminated aquifers to drinking water standards remains an impossible goal.

PERSPECTIVES

A significant proportion of the experience gained in the United States has been at sites at which remediation has been instituted under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA). The former is commonly known as the 'Superfund' Act because it established a federal government fund for remediating groundwaters at polluted sites. Without such a fund, which allows aquifer remediation to be initiated without legal liability for the pollution have been first established, it is unlikely that remediation will be applied widely in the UK.

A second issue related to the setting of goals or targets for remediation of groundwater. In most cases, groundwater quality targets established at Superfund sites have been the Drinking Water standards. However, at many sites these cannot be met with the existing technologies described above within a reasonable time and at a realistic cost. If less demanding targets are to be adopted, then the basis for these has to be established within the overall framework of environmental legislation and taking into account the water uses, health risks, available treatment technologies and financial constraints.

Recent government thinking on cleanup and funding are contained in the Framework for Contaminated Land.

BENEFITS AND BENEFICIARIES

The main benefits of research would be:

- cheaper and more effective clean-up.
- improved design criteria and protocols.
- improved guidelines on the specifications for clean-up contracts.
- improved monitoring of clean-up progress.
- greater assurance as to the effectiveness of clean-up.
- help to ensure that future changes in the law are pragmatic.

Beneficiaries would include:

- The NRA and the regulators in Scotland and Northern Ireland from help with the specification of contracts and with the design and monitoring of clean-up.
- Water Companies from long-term improvements to water quality and the consequent reduced cosvs of water treatment.
- Polluters from the reduced cost of clean-up and from the development of clear guidance and protocols.

- Developers and landowners where groundwater is subsequently found to be polluted.

RESPONSE

The NRA is currently having difficulty in enforcing remediation because (a) it is often difficult and expensive to identify the polluter, and (b) recovery of the full economic cost of remediation from the polluter is often not possible. Detailed monitoring during clean-up does not appear to be a high priority to the NRA.

R & D

- develop and improve remediation methods, including enhanced bioremediation
- analyse the effectiveness of different remediation strategies at a 'flagship' site
- develop advanced instrumentation for groundwater monitoring.

REFERENCES

DoE (1994). *Framework for Contaminated Land.* London: HMSO.

Gooddy, D.C. and A. R. Lawrence (1994). Groundwater contamination of the Chalk aquifer by the chlorinated solvents: A review of remediation techniques. *British Geological Survey Research Report SD/94/1*. Keyworth: British Geological Survey.

Grubb, D.G. and N. Sitar (1994). Evaluation of technologies for in-situ cleanup of DNAPL contaminated sites. *EPA/600/SR-94/120.*

Keely, J.F. (1989). Performance evaluations of pump and treat remediations. *EPA/540/4-89/005.*

MacDonald, J.A. and M. C. Kavanaugh (1994). Restoring contaminated groundwater: An achievable goal? *Environ. Sci. Technol.* 28: 362A-368A.

National Research Council (1994). *Alternatives for Groundwater Cleanup*. National Academy Press, Washington DC., pp 314.

Parker, B.L., R. W. Gillham and J. A. Cherry (1994). Diffusive disappearance of immiscible-phase organic liquids in fractured geological media. *Ground Water* 32: 805-820.

Authors: A R Lawrence, BGS
M E Stuart, BGS

Reviewer: P J Chilton, BGS
R J Flavin, NRA
A R Agg, FWR

RESOURCE PROTECTION AND VULNERABILITY

PROBLEM STATUS

Vulnerability is the degree of accessibility of an aquifer's saturated zone to the vertical penetration of pollutants from the land surface, and the pollutant attenuation capacity of the protecting strata and soil (IAH, 1994). There is currently a concerted effort to define land surface zones according to vulnerability classes and to model groundwater vulnerability to potential pollutants (NRC, 1993; Skinner and Foster, 1995). The problem is how to map vulnerability quickly over large areas, but at a useful scale, and using existing data.

The present UK approach to aquifer vulnerability mapping involves the production of general vulnerability maps whereas, in the past, effort had been largely restricted to a consideration of nitrate vulnerability (Robins *et al.*, 1994). Other criteria would apply to other chemicals. For example, the vulnerability of groundwater to acidification would depend not only on the hydraulic characteristics of the aquifer, but also on its acid buffering capacity. Vulnerability to other pollutants, such as pesticides and solvents, would weight different aquifer characteristics in different ways (Adams and Foster, 1992).

RELATED ISSUES

Contaminated land
Land-use change
Nitrate
Pesticides

TRENDS

The application of nitrate fertilizer to agricultural land in Britain has increased at a rate proportional to the intensification of farm practice over the past forty years. It was a long time before the agricultural community acknowledged the association between nitrogen application and rising levels of nitrate in groundwater, but full cooperation is now offered from this quarter. The use of agricultural pesticides has also increased in recent decades; some of the more persistent organic compounds are now being detected in groundwater supplies, and this problem could develop on an increasing scale as time goes on.

Point source pollutants derive from a variety of sources. Although greater care is taken today in preventing potential pollutants from gaining access to the ground and sub-strata, there remains accidental spillage and the legacy of earlier contamination only now finding its way to the water table. In the latter category are mine water rebound from the wholesale closure of mines, sanitary and industrial landfill, old landfill, contaminated land including mine wastes, ageing and leaking sewers, unprotected fuel stores, transport, and industry in general.

The increasing incidence of pollution of groundwater by chlorinated solvents (DNAPLs) and fuel oils (LNAPLs) reflects a trend that is likely to continue. The factors controlling the transport of these pollutants are likely to be different from those that are important for fertilizers and other agrochemicals.

CONTEXT CHANGES

Recent legislation has recognised the importance of protecting groundwater from surface pollutants, and a strict code of maximum admissible concentrations of both chemical ions and inorganic compounds has been established within EC law. The legal framework will continue to evolve with time.

Related issues include agricultural reform, improved and regulated landfill design and location, improved chemical and fuel storage facilities and their location, replacement of Victorian sewers, retention of pumps in abandoned mines, development of aquifer remediation techniques, etc. All these activities contribute towards reducing potential pollution. However, they will not prevent it completely and groundwater pollution will continue to be an increasingly important issue.

LEARNING CURVE

The major effort to date has been understanding the issues relating to elevated and rising nitrate concentrations in groundwater. This research has been well disseminated. It led directly to land management change. Work on organic pollution is only now beginning, and is still at the stage of recognising the potential magnitude of the issues involved. Although a great deal of research into point source pollution has and is being conducted, the need for further research grows at a rate faster than the rate at which work is completed and published.

This research provides the foundation for land surface zoning to define the vulnerability of underlying aquifers. A large variety of classification schemes has been put forward, from relative vulnerability indices to zonation of the hydraulic environment of the protective cover (Addiscott, 1977; Bachmat and Collin, 1987). These techniques are only now evolving and none have yet been put to the test of time. With each new scheme comes a list of caveats and improbabilities, and the need for further development is essential.

In Britain, the production of general aquifer vulnerability maps recognises that the role of low permeability drift in inhibiting percolating pollutants is largely unknown, and the adopted scheme ignores the time element of pollutant transport as too difficult to accommodate with available data.

PERSPECTIVES

In the UK, the issue affects the whole of the water industry, but in particular the National Rivers Authority, the Department of Environment for Northern Ireland and the Scottish Office. Regional and local planning authorities, industry and farmers may all have perspectives on this issue.

BENEFITS AND BENEFICIARIES

The most significant benefit of an enhanced understanding of groundwater vulnerability issues would be the enabling of more sophisticated resource protection policies. There are many potential beneficiaries, primarily groundwater regulators and the water supply industry but also planning authorities. The latter include both planning regulators as well as potential modifiers of land use.

RESPONSE

The British response is based on the National Rivers Authority Policy for the Protection of Groundwater (NRA, 1992). From this stems a classification system for land zonation which depends on the hydraulic conditions of the protecting cover. Already a 1:1 million map of England and Wales and a 1:250,000 map of Northern Ireland have been published. A series of 53 1:100,000 maps are being prepared for the NRA and a 1:625,000 map is being prepared for the Scottish Office.

Research into the role of superficial cover is being carried out for the NRA.

R & D

- develop classification of potentially polluting activities with respect to groundwater, based on risk assessment studies
- identify critical physical, chemical and biological factors controlling the transport of different classes of pollutants as a function of soil and geological conditions
- develop appropriate predictive transport models
- monitor the value of the published vulnerability maps as a groundwater management tool
- review and monitor vulnerability techniques developed elsewhere.

REFERENCES

Adams, B. and S. S. D. Foster (1992). Land surface zoning for groundwater protection. *Journal of the Institute of Water and Environmental Management*, 6: 312-320.

Addiscott, T. M (1977). A simple computer model for leaching in structured soils. *Journal of Soil Science* 28: 554-563.

Bachmat, Y. and J. Collin (1987). Mapping to assess groundwater vulnerability to pollution. In '*Vulnerability of soil and groundwater to pollutants*', eds. W. van Duijvenbooden and H.G. van Waegeningh. *TNO Committee on Hydrological Research, The Hague, Proceedings and Information No 38*, pp. 297-307.

IAH (International Association of Hydrogeologists) (1995). *Guidebook on mapping groundwater vulnerability*. Ed. Vrba, J. and Zaporozec, A. International Contribution to Hydrogeology, Vol. 16. Hannover: Heise.

NRA (1992). *Policy and practice for the protection of groundwater*. London: HMSO. pp. 52.

NRC (National Research Council) (1993). '*Groundwater vulnerability assessment: contamination potential under conditions of uncertainty*'. Washington, DC: National Academy Press. 198 pp.

Robins N. S., B. Adams, S. S. D. Foster and R. C. Palmer (1994). Groundwater vulnerability mapping: the British perspective. *Hydrogéologie* 3: 35-42.

Skinner, A. C. and S. S. D. Foster (1995). Managing land to protect water: the British experience in groundwater protection. In '*Proceedings of the International Association of Hydrogeologists 26th International Congress, Edmonton, Canada. June 1995*'.

Author: N S Robins, BGS

Reviewers: P J Chilton, BGS
B Adams, BGS
A C Skinner, NRA

SOURCE PROTECTION

PROBLEM STATUS

Prior to the establishment of the NRA, ten Regional Water Authorities (RWAs) were responsible for the management of the surface and groundwater resources of England and Wales. The Water Act of 1989 enabled the creation of ten private water and sewage undertakings (and continued the existence of twenty nine smaller statutory water companies) and also created the National Rivers Authority (NRA) to act as the regulatory authority for water resources. Before the 1989 Water Act was passed, several of the RWAs had published and/or operated their own groundwater protection policies. These differed from each other to varying degrees.

The NRA recognised an urgent need for groundwater protection policy to be harmonised nationally, and so the "Policy and Practice for the Protection of Groundwater" (NRA, 1992) was developed to meet the following objectives:

(i) To enable the NRA to meet their statutory responsibility to protect groundwater.

(ii) To provide a consistent approach to groundwater protection throughout England and Wales.

(iii) To disseminate the likely NRA response to planning and waste disposal applications.

The protection of groundwater quality is of critical importance for the following reasons (NRA, 1992):

- If groundwater becomes polluted it is difficult, if not impossible to rehabilitate. It is therefore better to prevent or reduce the risk of groundwater contamination than to deal with its consequences.
- Its major and ubiquitous use is for potable supply which means that a high quality standard must be maintained for all resources.
- Aquifers provide storage for considerable volumes of high quality water which requires little treatment prior to use, even for potable supply. The loss of this widely available low cost water resource would require more expensive water resource options to be developed.
- Groundwater provides the baseflow of many surface water systems. Some of these are used for potable, industrial and agricultural supplies as well as for recreational uses. For these reasons and others of general amenity and conservation, the quality of the baseflow is critical. Hence protection of

groundwater can be an important aspect of sustaining surface water quality.

Following publication of the NRA's Policy, source protection zones for a number of groundwater abstractions (wells and springs) have been defined using both manual methods and digital modelling software - normally the FLOWPATH code. This work highlighted a number of issues that will warrant further investigation (see R & D).

RELATED ISSUES

Deep waste disposal
Resource protection and vulnerability
Sealing abandoned boreholes

TRENDS

As more source protection zones are defined, experience in their definition is obviously increasing and issues are being discussed more widely (Adams and Foster, 1992; Adams *et al.*, 1994), thus the trend is generally towards an improved situation - ie a greater understanding of the problem(s). However increasing application of the NRA's Groundwater Protection Policy, by the NRA and others, will lead to increasing scrutiny of the methodology(ies) used to define source protection zones.

CONTEXT CHANGES

The EC's Groundwater Directive of 1980 (80/86/EEC) was chiefly aimed at the control of discharges of specified substances to groundwater. As only a limited number of substances were included and the issues of diffuse pollution, the need for management of abstraction and the requirement for monitoring were not addressed, the Directive's impact was somewhat limited.

Recognising the limitation of the existing community-wide regulations, a declaration by EC Environment Ministers in 1991 adopted an action programme for future protection of groundwater which stated that:

- groundwater resources are limited and should be managed and protected on a sustainable basis;
- it is essential to protect groundwater resources against over-exploitation, adverse changes in hydrological systems resulting from human activities, and pollution;
- water management policies should be integrated with the wider environmental framework as well as with other policies dealing with human activities such as agriculture, industry, energy, transport and tourism.

To support this EC objective of sustainability of groundwater quality and quantity through an integrated approach, the NRA published their new policy framework for protecting groundwater in 1992 (NRA, 1992).

The requirement to define recharge capture areas as part of the source protection strategy had also been a requirement for the definition of Nitrate Sensitive Areas (NSAs). NSAs were developed in response to the rising concentrations of nitrate in many groundwater sources used for public supply and the requirement of the Drinking Water Directive (80/788/EEC), which became UK law in 1985, to maintain concentrations in drinking water at or below 11.3 mg NO_3-N/l at the consumers tap. Ten pilot NSAs were established in 1990 within which farmers were encouraged to implement voluntary changes in agricultural practice, in return for agreed payments. An additional 22 NSAs were designated in 1993, covering a further 28 sources.

More recently, implementation of the Nitrate Directive (91/676) has required Member States to identify those areas in which the nitrate concentration of surface water or groundwater already exceeds 11.3 mg NO_3-N/l, or is likely to exceed this figure by the year 2010. Seventy-two of these areas, known as Nitrate Vulnerable Zones (NVZs), are currently being designated and where they are based on nitrate problems, extensive work on defining source protection areas was carried out.

An understanding of the methodology for capture zone definition is also relevant to another area of increasing environmental awareness, that of the protection of wetlands from pollution and, to a lesser extent, groundwater exploitation.

It is evident that increasing demand for groundwater coupled with ever increasing development demands on land-use will inevitably increase scrutiny of the methodology/ies applied to recharge capture area and source protection zone definition.

LEARNING CURVE

Since the publication of the NRA's Groundwater Protection Policy, the definition of source protection zones for over 800 of the most important groundwater abstractions in England and Wales has led to a wider understanding of the issues involved and the modelling methodologies used (principally that of FLOWPATH). Some attempt has been made to address the issue of parameter uncertainty (Geraghty and Miller for the NRA, unpublished). Generally, however, the issues noted under PROBLEM STATUS have not been addressed in depth.

PERSPECTIVES

Where groundwater is a major source of supply either regionally or locally, protection of the resource is vital for both the consumers and the economic life of the Water Supply Company.

In addition to source protection measures taken, operators need to secure the long-term viability of their sources by carrying out risk assessment, implementing monitoring strategies and, where necessary, provide additional treatment facilities.

BENEFITS AND BENEFICIARIES

The main benefit from research in this area will be increased confidence in the source protection zones defined to implement the NRA's Groundwater Protection Policy, and the Nitrate Sensitive and Nitrate Vulnerable areas defined as a result of the EC AgriEnvironment Regulations and Nitrate Directive (91/676). Thus the NRA will benefit by having a robust set of source protection zones and Nitrate Sensitive/Vulnerable areas which will be less open to challenge. The private water companies will benefit by having their sources effectively delineated for protection purposes.

RESPONSE

As the NRA establishes source protection zones across England and Wales, many of the water companies have purchased the FLOWPATH computer code to both check the NRA's zones and, in some cases, to develop zones for sources not yet covered by the NRA. Both the NRA and the water industry are looking at the suitability of other digital models to define source protection areas - eg MODFLOW/MODPATH - and existing aquifer models of specific regions.

Water companies are using source catchment areas to prioritise pollution risk assessment measures.

R & D

- evaluate the significance of transient aquifer behaviour as a result of recharge variations when using steady state models
- review the validity of long, thin protection zones for small abstractions in low porosity aquifers and the further development of methodology if required
- assess 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.
- The change in shape/size from previously determined empirical zones - ie prior to the national policy.

REFERENCES

Adams, B. and S. S. D. Foster (1992). Land-surface zoning for groundwater protection. *J.Inst. Water Eng. Manag.* 6:312-320.

Adams, B., J. A. Barker and D. M. J. Macdonald (1994). Considerations in the implementation of a groundwater protection policy. In *'Proceedings of IBC Conference on Groundwater Pollution'*. London, March 16-17.

National Rivers Authority (1992). *Policy and Practice for the Protection of Groundwater*. pp 52. London: HMSO.

Author: B Adams, BGS

Reviewers: I N Gale, BGS
B L Morris, NRA
A R Agg, FWR
J Flude, Dynamco Ltd
R Rodgers, Severn Trent Water Ltd
P Aldous, Thames Water Ltd

SUSTAINABLE YIELD

PROBLEM STATUS

Groundwater must be managed as a sustainable resource. Quantities of water authorised for abstraction must be balanced against the recharge to the aquifer and assessed against the environmental needs of rivers to sustain baseflow as well as other features reliant on groundwater such as wetlands. Historic development of groundwater resources in some areas has been well within the sustainable yield of the aquifer in question, so development has only resulted in very localised problems. However, in other areas groundwater resources have been developed beyond their sustainable yield resulting in aquifer dewatering, reduction or cessation of baseflow to streams, contraction of wetlands and saline intrusion into coastal aquifers.

As demand for groundwater increases, and environmental pressures grow, aquifer management needs to become increasingly sophisticated. In many instances this has required computer models supported by comprehensive data collection to calibrate the models (eg Rushton *et al.*, 1989). Nevertheless, many assessments of the sustainable yield of groundwater resources are still made on relatively simple analyses of inputs to and outputs from aquifers.

Because of the limitations of the methods used to assess the sustainable yield of groundwater resources, regulators in some areas have erred on the conservative side and have refused to licence additional abstraction. The problem has been compounded by the inflexibility of the licensing system where it is difficult to redistribute unused licence quantities. In exceptional circumstances drought orders may restrict the use of a licence.

Current practice for assessing the sustainable yield of an aquifer has evolved in response to varying demand and availability of resources; little attention has been paid to designing a national methodology. Additionally, little consideration has been given to the comparison of the results obtained using different methodologies or the impacts of spatial and temporal variation of recharge.

The hydraulics of groundwater in the unsaturated zone in both intergranular and fractured aquifers is not well understood. The role of delayed storage in this zone may play an important role in the determination of the sustainable yields of aquifer.

RELATED ISSUES

Source protection

TRENDS

Demands for abstraction licenses where groundwater is already well developed are not being granted in some areas. This is partly due to a lack of accurate knowledge of the inputs to, and the outputs from the system and partly because existing licensed abstraction exceeds the calculated sustainable yield even though the actual abstraction is well below this level.

As demand for groundwater increases, and deterioration of quality restricts use of some parts of aquifers, increasingly sophisticated resources management practices will need to be developed. These techniques cannot be employed unless sufficient data are available on which to base management decisions. Increasingly, the resources available for exploitation in relation to environmental demands will need to be quantified more accurately and increasingly complex and innovative integrated surface and groundwater schemes will need to be developed.

CONTEXT CHANGES

The ability of groundwater to be used on a sustainable basis is affected by changes in:

- Demand
- Climate
- Legislation - eg abstraction licences in Northern Ireland and Scotland.
- Quality (pollution).

LEARNING CURVE

Sustainable yield and estimation of recharge have been investigated by hydrogeologists in many parts of the country (eg Owen *et al.*, 1991). Differing methodologies of recharge estimation are being reviewed and a unified methodology will evolve from a current NRA sponsored project (R&D Project 499) which is due to report in March 1995. A parallel project recently commissioned by the NRA will recommend national methods for assessing the theoretical renewable resource potential of selected aquifers. UK WIRL is currently funding projects on outages and groundwater yields, which will add to our knowledge on the subject.

PERSPECTIVES

Both the guardians and the users of groundwater resources would benefit from more accurate estimates of sustainable yield. The NRA need a more systematic basis for approving licensing of groundwater resources in England and Wales. In Scotland and N. Ireland, licences are not yet required, but as pressure to exploit groundwater increases so the need to know the sustainable yields of aquifers will increase. Water companies need to be able to develop optimum management strategies to utilize the available groundwater resources whilst minimising environmental impacts and costs.

BENEFITS AND BENEFICIARIES

The benefits of improved methods of assessing the sustainable yields of aquifers are a better understanding and quantification of the components of the water cycle. This should provide a sound, nationally defensible basis for the effective development and management of groundwater resources and for the maintenance of baseflow and wetlands at acceptable levels.

The groundwater users are the ultimate beneficiaries of research into assessment of sustainable yield of groundwater resources. The NRA and Environmental Agencies will be able to manage the resources better and the water companies will have a clearer understanding of the resources they utilize.

RESPONSE

National systematic approaches are being developed to assess recharge to aquifers as well as improved methods of sustainable yield assessment to accommodate temporal variability of natural discharge and abstraction. The water industry is adopting increasingly sophisticated techniques to utilize the resources available to them including artificial recharge, seasonal pumping and water transfer.

R & D

- carry out an in-depth review of operational experience
- investigate the importance of the unsaturated zone for drought storage
- further develop stochastic water resource models
- develop methods for estimating the spatial variability of recharge
- determine the amount of storage in drift and leaky aquitards.

REFERENCES

Owen, M., H. G. Headworth and M. Morgan-Jones (1991). Groundwater in basin management. In *'Applied Groundwater Hydrology'*, eds. R. A. Downing and W. B. Wilkinson. Oxford: Clarendon Press. pp. 16-34.

Rushton, K. R., B. J. Connorton and L. M. Tomlinson (1989). Estimation of the groundwater resources of the Berkshire Downs supported by mathematical modelling. *Quart. J. Eng. Geol.* **22**: 329-341.

Author: I N Gale, BGS

Reviewers: N S Robins, BGS
R I Rodgers, Severn Trent Water Ltd
B D Misstear, Trinity College, Dublin
D B Burgess, NRA - Anglian
R Sage, Thames Water Ltd

WETLAND CONSERVATION

PROBLEM STATUS

In wetland areas, ecology, microclimate and even the local economy depend on the presence of excess water (Gilman, 1994a). Wetland soils are at least periodically saturated, and wetland plants are adapted to the problems posed by saturation, particularly oxygen depletion and the build-up of toxic products from the anaerobic decomposition of dead plant material. Many natural wetlands, though highly productive in the ecological sense, have been subjected in the interests of development to drainage, "reclamation" and non-sustainable exploitation which has left wetland areas severely depleted on a world scale.

Remaining wetland habitat in the UK is protected by designation of individual sites, but continuing development pressure frequently raises the question of the balance between conservation values and the impact of external forces: it can often be difficult to provide necessary scientific evidence to support unequivocal assertions relating to the impact on a particular site. The habitat value of wetlands is almost invariably linked to a pattern of hydrology and hydrochemistry that has been stable over the long term, and short term disturbances to this pattern can have important consequences to the composition and diversity of the ecosystem.

Most wetlands occur in areas of little understood geology and hydrogeology, often in areas underlain by superficial and weathered materials. A more detailed understanding of wetland processes and functions is needed for a full appreciation of the value of wetlands, both as sustainable reserves of wildlife and their habitats and as components of the hydrological system with a recognisable function, for example in the maintenance of streamflows and surface water quality.

RELATED ISSUES

Low flows
Sustainable yield

TRENDS

Several conflicting trends appear to maintain a constant rate of development threat towards wetland sites, but an increasing demand for scientific sophistication in mitigation measures:

(i) increasing pressure for building development (roads, shops, factories and houses) on floodplain sites. As a result of high land values and costs of reclaiming derelict land, developers tend to favour the use of wetlands, particularly meadows. While designated sites are usually protected from direct impact, development of peripheral land can also have important effects.

(ii) development pressures are likely to be deflected from other areas of potential conflict. For example groundwater abstractions may be increasing locally.

(iii) the impact of agricultural drainage and reclamation is lessening as a result of changed financial inducements, but some threats associated with agriculture remain, for instance pesticides and nutrient-enriched runoff, while long-term effects consequent on drainage will continue to be detected, particularly on peatland sites.

(iv) developers are reluctant to be seen to destroy wetland sites, but good scientific support is essential for schemes which promise impact mitigation, replacement of wetlands lost, or the provision of new amenity wetlands. Over the next two decades, there will be an increasing tendency to base the evidence for and against development on the results of earlier schemes; post-construction monitoring will become a more important condition of planning consent.

CONTEXT CHANGES

Increased groundwater abstraction within units that are not already fully exploited, and consideration of affected wetland sites will become a common feature of licensing procedures. Appreciation of the hydrological and hydrochemical function of wetlands, particularly in riparian zones, will increase the value of such sites. In the face of increased abstractions from downstream reaches of rivers, and pressures for improved river water quality, there will be an increase in the use of artificial wetlands for secondary and tertiary treatment of water, and these will require scientific management to maximise both treatment capability and useful life. Research will be required into their hydrological behaviour (response to rainfall and climatic variations) and hydraulics (processes of water movement through the substrate, and temporal changes in hydraulic properties).

Conservation bodies will continue to seek designation of internationally important wetlands to ensure their wise use. The preservation of wetlands is included in the Convention on Biological Diversity signed by the UK at the 'Earth Summit' in Rio de Janeiro in June 1992 (Department of the Environment, 1994). International interest has the effect of raising the profile of potential conflicts, and adds to the demand for scientific expertise in resolving these conflicts.

Though climate change will inevitably effect the prospects of wetland conservation, it is difficult to point to specific effects with immediate relevance to the groundwater aspects of wetlands. However, very few UK wetlands are "natural" in the sense that most are remnants of a previous less efficient agricultural economy. Clearly climate change will affect the water budget, both annually and seasonally, but our understanding of the relationships between the overall water budget and the detailed hydrology of individual wetland sites is imperfect. Of particular interest in this context, and covered by remarkably little research, is the impact on wetland habitats of short sequences of drought years. An increase in the frequency of such years, in keeping with reduced summer rainfall, could have important effects on sensitive communities, but there is little information on the response of such species to the climatic fluctuations that are now experienced by wetlands.

The peat in UK wetlands is a major store of organic carbon (our 'tropical forests') that need to be preserved and even enhanced to reduce our contribution to the increasing concentration of CO_2 in the atmosphere and any consequent effects that may have on climate.

LEARNING CURVE

The water budget of a wetland area demonstrates the central importance of groundwater in wetlands. It is known that there are flows of water between the wetland's saturated zone, usually located in organic silts or peat, and the deeper regional groundwater body, between the saturated and unsaturated zones and between open water bodies and the deep aquifer. These flows can be disrupted by development, leading to dramatic changes in the quality of wetland habitat and in the behaviour of wetlands in response to hydrological events. As an added complication, some plants, the phreatophytes commonly found in wetlands, can draw directly on the saturated zone for water and nutrients.

There is a wide range of literature on the relationships between wetland conservation and groundwater. Much of this work relates to the US. Gilman (1994b) has recently reviewed the area as part of a broader study of water balances in wetland areas.

PERSPECTIVES

- Public perception and prejudices (SSSIs etc)
- Resources - NRA, Water Companies; RPBs, Regional Councils, DoE NI
- National bodies : National Trust etc

BENEFITS AND BENEFICIARIES

There is a need to reconcile the demands of potential developers as ecosystem conservation for long-term sustainable development. The objectives should be for:

- improving the precision of prediction of impacts, and improving our chances of avoiding unnecessary damage to the environment, while not precluding developments that could proceed without serious harm being done.

- reducing the cost of the measures that are regarded as necessary to protect the environment, by progressively refining techniques for prevention and mitigation of impact, and making good use of past experience.

- supporting the concept of sustainable or wise use of the environment, by getting over the message that development and a good human and natural environment are not mutually exclusive.

A more complete understanding of these topics are spread over the whole range of development and conservation from the Government (eg MAFF, DoE, DTp) and planning authorities (including the NRA), through commercial developers to the conservation community (including English Nature, the Countryside Council for Wales and Scottish Natural Heritage).

RESPONSE

There have been a number of recent Government initiatives in which the conservation of wetlands play a part. For example, many of the existing wetlands are designated as Sites of Special Scientific Interest (SSSI's). Some of the wetlands, particularly in Wales, are targeted habitats for conservation under the Environmentally Sensitive Areas programme of the CAP. Sixty eight wetland areas of international quality had been designated under the Ramsar Convention by November 1993 (Department of the Environment, 1994).

Water level Management Plans are being prepared for wetlands within drainage systems with priority given to those of high nature conservation interest. English Nature, Internal Drainage Boards, the NRA and individual landowners are involved in the process, and MAFF is involved in encouraging their activities. The objective is to provide an agreed procedure for the management of water levels in order to ensure that the conditions are favourable to wintering and breeding birds and for characteristic ditch and meadow plants and invertebrate animals.

A project on the hydrodynamics of groundwater-fed wetlands in East Anglia was carried out by the University of Birmingham, with support from the NRA, NCC and the Broads Authority (Gilvear *et al.*, 1993). The impact of groundwater abstraction on East Anglian wetland sites is currently being investigated by a joint IH/BGS project funded by the NRA (Anglian Region).

R & D

- quantify the water requirements of wetland flora and the range of soil moisture conditions that can be tolerated

- carry out strategic monitoring of wetlands

- assess the hydraulic properties of wetland soils and the processes of groundwater movement within the shallow saturated zone

- analyse the extent of surface water-groundwater interaction, and an improved understanding of valley bottom wetland hydrogeology at selected sites

- establish the relationship between flows of water within wetlands and the spatial and temporal variations in water quality

- develop ways of classifying the vulnerability of wetlands.

REFERENCES

Department of the Environment (1994). *Biodiversity: the UK Action Plan.* Cm 2428. London: HMSO.

Gilman, K. (1994a). *Hydrology and wetland conservation.* Chichester: Wiley & Sons.

Gilman, K. (1994b). Water balance of wetland areas. In *'The balance of water - present and future'*, ed. T. Keane and E. Daly, Proc. AGMET/Roy. Met. Soc. Conf., Dublin, pp. 7-9.

Gilvear, D.J., R. Andrews, J. H. Tellam, J. W. Lloyd and D. N. Lerner. (1993). Quantification of the water balance and hydrogeological processes in the vicinity of a small groundwater-fed wetland, East Anglia, UK. *J. Hydrol.* **144**: 311-334.

Author: K Gilman, IH

Reviewers: N S Robins, BGS
A R Agg, FWR
J W Lloyd, University of Birmingham
D Burgess, NRA
K S Wilson, Ready Mixed Concrete (UK) Ltd
I H MacDonald, DoE

OTHER ISSUES

ACIDIFICATION

PROBLEM STATUS

Because of the buffering provided by most rocks, groundwaters are invariably less acidic than the corresponding surface waters. For example, groundwaters are rarely more acidic than pH 5.5. Nevertheless, the gradual acidification of groundwaters resulting from acidic atmospheric deposition is a regional (European scale) problem which can affect aquifers with poorly buffered lithologies (Jacks *et al.*, 1984; Holmberg *et al.*, 1990). The problem is widespread in Scandinavia but most major UK aquifers are well buffered and unlikely to be significantly affected. This applies to all aquifers containing calcium carbonate either as a major component (chalk and other limestones) or as a minor component (sandstones).

Where there are thin, acid soils with shallow unsaturated zones, shallow groundwaters could be affected and although these groundwaters are not used for major public supplies, they are important for contributing alkaline baseflow to streams and for supplying many private sources in rural areas. Changes to this shallow groundwater are likely to occur slowly and be difficult to detect. The first signs are likely to be an increased concentration of base cations and sulphate and a reduction in groundwater alkalinity (Holmberg *et al.*, 1990). Only when most of the alkalinity has been neutralized will the pH change significantly and increased solubilization of metals such as aluminium occur.

In some cases, groundwaters may be acidic due to the internal generation of acidity. This is invariably due to oxidation reactions, usually of pyrite, FeS_2. Acid mine drainage is an example.

The most significant economic impact of the continued acidification of shallow groundwaters is the increased rate of corrosion of underground pipes and other metallic structures.

RELATED ISSUES

Acid mine drainage
Afforestation
Heavy metals

TRENDS

Although neutralisation of rainfall acidity by water-rock interaction is a natural process that occurs over geological timescales, rates of weathering may have increased by an order of magnitude over the past 40 years due to increased emissions of SO_2 and NO_x gases from fossil fuel burning power stations and cars. There are at present insufficient data to establish trends in the acidification of groundwater, or even to confirm the rates of reaction in different lithologies. High emissions of NH_3 from intensive animal rearing may exacerbate the acidification problem locally since the NH_3 is subsequently deposited on vegetation, especially forests, and then oxidized to nitric acid.

There has been a steady overall decline in SO_2 emissions since the early 1970's and this is set to continue. These reductions have been greatest near industrial areas and in part reflect the decline in industrial activity. However, there has not been a corresponding reduction in atmospheric SO_2 concentrations in many of the most acid-sensitive areas. There is also a steady increase in NO_x emissions (60% from cars) which is tending to counteract these SO_2 reductions.

CONTEXT CHANGES

The acidification of groundwater interacts with several other aspects of the hydrological cycle. Buffering of streams and lake waters by near-neutral groundwater has helped to offset some of the effects of surface water acidification in Britain (Cook *et al.*, 1991). Since shallow groundwaters are the most vulnerable, any reduction in their alkalinity could affect the ability of the groundwater to reduce the acidity of surface waters.

Areas chosen for landfills are often sites that are most vulnerable to acidification. Therefore these sites are important to consider in the overall context of groundwater protection. Acidification will tend to enhance the mobility of most metals through soils and the unsaturated zone.

Since the rate of leaching of base cations from soils and aquifers is related to the total flux of acidity, acidic deposition must also be considered in terms of the fluxes involved, ie the concentration of H^+ multiplied by the amount of rainfall. Some of the areas with the highest fluxes lie in high rainfall areas of the highlands rather than in the lowlands which are nearer to the emission source but receive less rainfall. At present acidification of waters, both surface waters and groundwaters, has a high profile with the European public and this is likely to continue. Monitoring programmes are at present inadequate to assess any changes that are taking place in the shallow groundwater environment.

LEARNING CURVE

The overall UK situation is now well defined and the extent of the problem has been published. Further specific research is still needed as defined below. Better dissemination of the nature of the problem and of the work to date is desirable.

It is clear that over large areas of the UK, carbonate lithologies offer almost unlimited acid neutralising capacity. Vulnerable areas have been defined on the basis of bedrock geology. It is known that acidic groundwaters are most likely to be found where: (i) acid soils are found and glacial drift is thin or absent; (ii) acidic inputs are high; (iii) carbonate minerals are absent; and (iv) the residence time of water is short. The main areas at risk include many Lower Palaeozoic and older strata, granites and especially parts of the Lower Greensand, Sherwood Sandstone and other sandstone or grit lithologies.

In dual porosity aquifers, bypass of unbuffered water may lead to seasonal pH changes in shallow springs and wells. Where the unsaturated zone is well developed (eg in sandstones and some unconsolidated aquifers), mobilisation of aluminium and other metals may occur in the upper part of the unsaturated profiles. Base cations held on exchange complexes are gradually removed as acidic water moves towards the water table.

Current monitoring programmes are geared towards the major groundwater sources and do not take sufficient account of the changes taking place in smaller sources, often private and unregulated supplies.

A large amount of acidity is currently stored in acidic soils and the future rate of release of this to groundwater is not well understood. Most agricultural soils are limed if they are acidic (pH less than 5.5-6.0) and this will reduce the acidity of water infiltrating to the underlying aquifer. However, upland pastures are not generally limed. There was a sharp decline in the use of agricultural lime between 1965 and 1980 (Kinniburgh and Edmunds, 1986). The lime subsidy was ended in 1976.

PERSPECTIVES

The main group with an interest in this field are the UK Water Undertakers. However the threats to changing habitats and river water quality make the issue of wider interest to Environmental Groups and Agencies. In acid-sensitive areas, the streams and rivers can depend on an underlying contribution of alkalinity from the groundwater baseflow to neutralize some of the acidity.

The increased rate of corrosion of underground pipes and structures in acidic groundwaters is of concern to the individuals and organizations involved.

BENEFITS AND BENEFICIARIES

Increasing acidification of the environment including that of shallow groundwaters only has an obvious and direct impact where remedial actions are required to maintain good quality water supplies. The construction or deepening of wells and boreholes may be required in rural areas currently served by natural springs and shallow wells. Acidification of groundwaters will also have an indirect impact on streams, rivers and lakes due to the loss of buffer capacity (alkalinity) in the baseflow.

RESPONSE

Remediation of acidification waters (lakes and streams) has been attempted over the past decade by lining lakes and soils. This treatment is often harsh and may damage the ecosystem. The use of alkaline groundwater although demonstrated to be feasible Cook *et al.* (1991) needs to be tested, both as a means of treating lakes and also as an alternative to the use of very shallow groundwater for supplies.

Trends in the acidity and chemistry of upland water are currently being monitored through the Acid Waters Monitoring Network funded by DoE.

R & D

- monitor shallow groundwater sources in key vulnerable areas to identify any adverse trends in HCO_3, pH, SO_4, Al and other metals
- assess the extent of acidification in selected private water supplies in susceptible areas of the UK
- determine the rates of movement of acid fronts and associated metals in the unsaturated zone of vulnerable areas
- develop and validate geochemical models for predicting the time-scale and extent of groundwater acidification and its ability to be reversed.
- monitor the water quality trends in surface waters over the past two decades (including lakes) to identify underlying changes

REFERENCES

Cook, J. M., W. M. Edmunds and N. S. Robins (1991). Groundwater contribution to an acid upland lake (Loch Fleet, Scotland) and the possibilities for amelioration. *J. Hydrol.*, **125**: 111-128.

Edmunds. W. M., D. G. Kinniburgh and P. D. Moss (1992). Trace metals in interstitial waters from sandstones: acidic inputs to shallow groundwaters. *Environ. Poll.* **77**: 129-141.

Edmunds, W. M. and D.G. Kinniburgh (1986). The susceptibility of UK groundwaters to acidic deposition. *J. Geol. Soc. London* **143**: 707-720.

Holmberg, M., J. Johnston and L. Maxe (1990). Mapping groundwater sensitivity to acidification in Europe. In '*Impact Models to Assess Regional Acidification*, ed. J. Kämäri. Chapter 4, pp. 51-64. Dordrecht: Kluwer.

Jacks, G., G. Knutsson, L. Maxe and A. Fylkner (1984). Effect of acid rain on soil and groundwater in Sweden. In '*Pollutants in Porous Media*', ed. B. Yaron, G. Dagan and J. Goldschmid. Ecological Studies 47, pp. 94-114. Berlin: Springer-Verlag.

Kinniburgh, D. G. and W. M. Edmunds (1986). *The susceptibility of UK groundwaters to acid* *deposition*. Hydrogeol. Rep. British Geol. Surv. 86/3. Keyworth: British Geological Survey. 208 pp.

Author: W M Edmunds, BGS

Reviewer: D G Kinniburgh, BGS

BOREHOLE EFFICIENCY & REHABILITATION

PROBLEM STATUS

Many borehole owners/operators are not properly aware of the condition and efficiency of their water supply and monitoring boreholes. The borehole and associated infrastructure are the vital link between the groundwater resource and its use, and as such need to be given proper attention. The integrity of information obtained from monitoring and sampling boreholes is also as important. In aquifers such as the Chalk, where large diameter uncored boreholes and shafts are the main source of supply, the problem is not considered to be significant. However, where cording and screen are used in the productive zones, corrosion and encrustation can be significant as can the integrity of the coring and grout seals designed to protect the groundwater from surface contamination.

RELATED ISSUES

Source protection

TRENDS

Recent regard to Asset Management Plans (AMPs) by the water industry has focused attention on the condition/life and efficiency of all water industry infrastructure including out-of-sight, out-of-mind boreholes.

The UK water industry have followed the American water industry by recently (1993) commissioning a CIRIA report on the monitoring, maintenance and rehabilitation of water supply boreholes.

CONTEXT CHANGES

Greater demand in the water industry for improved efficiency is leading to consideration of improved monitoring, operation and maintenance of boreholes.

Resource management decisions will in some areas restrict the establishment of new groundwater abstraction points. Increased groundwater abstraction (up to licensed quantities) will then have to be realised through improvements to existing boreholes.

LEARNING CURVE

There is little experience in applying proper cost benefit analysis to monitoring and maintenance strategy development.

Some maintenance and rehabilitation methods, although widely used, are still not that well understood. The same applies to some of the processes which affect borehole condition/performance and therefore efficiency (Howsam, 1990; Borch *et al.*, 1993).

Relatively little detailed research has been conducted into cause and cure processes affecting the performance/condition of water supply boreholes. Up to date reviews of the subject are covered in the CIRIA and AWWARF references given below. The best examples of studies are from The Netherlands (KIWA) and North America (AWWARF). In the UK some studies have been conducted funded by the Wolfson foundation, ODA (Engineering Division), DTI and CIRIA.

PERSPECTIVES

The water industry would regard any improvement in efficiency and long-term security of sources, with attendant cost savings, favourably. Additionally, information on the cost effectiveness of different methods of rehabilitation of boreholes is needed to enable correct decisions to be taken.

BENEFITS AND BENEFICIARIES

Borehole operators will benefit from a more efficient and secure supply and improved groundwater source management, both in practical as well as economic terms resulting in better levels of service. Groundwater resource managers will benefit from reliable data from monitoring boreholes whose condition and integrity is known and is properly maintained.

RESPONSE

The water industry commissioned CIRIA to prepare a guide-line document on the 'Monitoring, maintenance and rehabilitation of water supply boreholes'. The report is to be published in early 1995 (Howsam *et al.*, 1995). Borehole operators are at various stages of developing or revising their strategies with respect to this subject.

R & D

- review and evaluate the economic benefits of borehole rehabilitation.

REFERENCES

Borch, M. A., S. A. Smith and L.N. Noble (1993). *Evaluation and restoration of water supply wells.* Denver: American Water Works Association Research Foundation (AWWARF) Publication.

Howsam, P., B. D. R. Misstear and C.R. Jones (1995). *Monitoring, maintenance and rehabilitation of water supply boreholes.* London: Construction Industry Research & Information Association (CIRIA) Report 137.

Howsam, P. (Ed.) (1990). *Water Wells - monitoring, maintenance and rehabilitation.* London: E.& F.N. Spon.

Author: P Howsam, Silsoe College

Reviewers: I N Gale, BGS
R Herbert, BGS
B D R Misstear, Mott MacDonald
R I Rogers, Severn Trent Water Ltd
J Flude, Dynamco Ltd
A R Agg, FWR
M O'Shea, Thames Water Ltd

CLIMATE CHANGE

PROBLEM STATUS

Although the impacts of climate change on groundwater are uncertain, there is now wide agreement that significant changes are likely to occur over the next few decades so strategic planning is essential. The impacts on water resources will be complex due to the numerous interactions between climate, demands and resources (Leavesley, 1994; Arnell, 1994).

RELATED ISSUES

Sustainable yield
Low flows
Saline intrusion
Wetland conservation

TRENDS

Based on best current predictions of climate change, effects on water resources can be inferred but are not certain.

Recharge in winter is likely to increase due to wetter winters. Anticipated changes in summer rainfall are less certain with no change being perhaps the most likely scenario. However, hotter drier summers and warmer autumns could eliminate summer recharge and delay the onset of winter recharge. Warmer summers would increase demands; irrigation, in particular, is likely to be more intense and widespread. Increased concentrations of carbon dioxide in the atmosphere may lead to a decrease water use by plants and might thereby tend to increase groundwater recharge.

Pressures on resources will increase generally but will be most strongly felt in the south and east of the UK. Droughts could become more common in all regions. However, this broad picture is over simplistic due to factors such as variability across the UK and inter-basin transfers.

Increased demand for groundwater will not only reflect the above mentioned effects but also the consequent reduction in the quantity and reliability of surface sources. Seasonal resource management will become of increasing importance.

A change in soil structure may occur which could lead to greater leaching, less water absorption and changes in applications of fertilizers and pesticides; adverse effects on groundwater quality could follow. Increased irrigation would exacerbate the effect. A greater frequency of intense winter rainfall would tend to increase direct recharge in winter and hence increase vulnerability to pollutants.

Wetlands will be under threat due to the greater fluctuations in groundwater levels and lower baseflows in rivers.

Groundwater levels and quality near coasts and estuaries could be affected by rises in sea level; the coastal towns of Sussex, Yorkshire and Lincolnshire could be particularly affected. (The sea level will rise primarily because of the thermal expansion of the ocean and the melting of glacier ice.)

LEARNING CURVE

The likely evolution of the UK climate is not known other than as probable scenarios suggested by climate models based on various assumptions. Most scenarios suggest that the changes in climate parameters indicated in Table 1 are likely (e.g. CCIRG, 1991).

In the past, such predictions have varied widely from one model to another and even current climatic conditions have not been adequately predicted. However, recent simulations by the Hadley Centre for Climate Prediction & Research (Meteorological Office), incorporating atmospheric aerosols, show a much improved fit to the observed global mean temperature over the last 100 years. It should be noted that global climate models work on very coarse grids (100 km squares are common) so spatial variations, even at catchment scale, are not revealed.

Whether or not the overall change in recharge will be positive or negative is different for different scenarios and depends critically on whether predictions of hotter, more droughty summers are offset sufficiently by increased winter rainfall. This varies from one model to another. Although most agree in predicting drier soils in summer, not all suggest an overall increase in winter recharge (Atkinson and McGuire, 1990; Countryside Commission, 1995).

Recent research into the likely impacts on coastal aquifers suggest that the threat of saline intrusion, due to sea level rise, affecting existing groundwater abstractions is small. Clark *et al.* (1992) suggest that safe yield pumping rates need only be reduced one or two percent; the alternative of moving sources inland would incur costs which are relatively small in comparison with those for ongoing maintenance and exploration. However, in coastal regions even small impacts may be relatively strongly felt due to the presence of: a large population, manufacturing industry, energy production facilities, and valued environments (especially beaches and wetlands).

Information relevant to future trends might possibly be obtained by study of the palaeohydrological record as observed, for example, in lake sediments and deep aquifers. Long-term records of piezometric levels and other hydrological data are also relevant to assessment of impending change, but their value is uncertain.

Arnell *et al.* (1994) list both completed and current research projects relating to climate change which are of relevance to the NRA. Past activity in climate research has been relatively high in recent years and, now that climate change scenarios with significant impact potential are widely accepted as likely (albeit subject to great uncertainty), research has begun to move on from the climate development to the prediction of impacts under various scenarios (Arnell *et al.*, 1994, list 5 coordinated programmes). However, little current research is directly concerned with assessing the impacts of potential climate change scenarios on groundwater resources.

The following broad initiatives deserve mention. The Climate Impacts LINK project, established by DoE, is a joint operation between the Hadley Centre and the Climatic Research Unit (CRU) with the primary aim of interpreting outputs from General Circulation Models (GCMs) and providing data in forms most suitable for impact studies. The DoE Core Model Programme (Parr and Eatherall, 1994) has as its main emphasis a demonstrator project describing the process of model building leading towards a series of core models for predicting the impact of climate changes on natural resources.

The NERC Terrestrial Initiative in Global Environment Research (TIGER) began in 1991. It aims to improve understanding of the processes that determine the structure and functioning of terrestrial ecosystems and their interaction with the global climate system. The Environmental Change Network (ECN) is a long-term, multi-agency, integrated environmental monitoring programme which is managed by NERC on behalf of a group of national sponsoring organisations.

PERSPECTIVES

The NRA has determined that any response which it makes to climate change should be guided by due consideration of the precautionary approach.

BENEFITS AND BENEFICIARIES

Almost all sectors of the water industry (as well as the agricultural sector) and in turn the public will benefit from research and monitoring to aid the planning of strategic responses to climate change.

RESPONSE

The response to the 'threat' of climate change has to some extent been delayed on the basis that impacts remain uncertain and are not likely to be felt within planning horizons. However, the commissioning of numerous impact studies indicates that complacency is not widespread. In particular, the IPCC has been encouraging climate change impact studies since 1988 by assessing the state of results and evolving response strategies (IPCC 1990, 1995a, 1995b).

R&D

Work in the following areas is required:-

- Development or identification of suitable catchment models and regional aquifer models and their application to various climate scenarios.
- Establishing better relationships between rainfall and recharge.
- Understanding and quantifying the likely changes in soil structure (especially the cracking of clays) and consequent vulnerability to pollutants require examination.
- Study of the palaeohydrological record as observed, for example, in lake sediments and deep aquifers.
- Databasing of long time series of data.
- Study of the potential for river augmentation, conjunctive use, cyclic storage in deep aquifers and other approaches to using higher winter recharge to meet higher summer demand.
- Investigation of the potential of groundwater to provide domestic supply while (lower quality) river water provides for increasing irrigation demand.
- Continued investigation of the concept of the disposal of carbon dioxide into deep aquifers and other reservoirs.

REFERENCES

Arnell, N. W., A. Jenkins and D. G. George (1994). The implications of climate change for the National Rivers Authority. *National Rivers Authority R&D Report* 12. Bristol: National Rivers Authority. 94 pp.

Arnell, N. W. (1994) Impact of climate change on water resources in the United Kingdom: Summary of project results. Report to DoE Water Directorate.

Atkinson, T.C. and F. McGuire (1990). Chapter 5 : Impacts of sea-level rise on coastal hydrology. In: The Effects of Sea Level Rise on the United Kingdom Coast. Research Report No.7, National Power plc and PowerGen plc, prepared by the University of East Anglia, School of Environmental Sciences.

Countryside Commission (1995). Chapter 8 : Impacts of climate change on water balance and water resources. In: Climate Change, Acidification and Ozone : Potential Impacts on the English Countryside. Report CCP458 Countryside Commission.

CCIRG (Climate Change Impacts Review Group) (1991). *The potential effects of climate change in the United Kingdom*. HMSO: London.

Clark, K. J., L. Clark, J. A. Cole, S. Slade and N. Spoel (1992). Effect of sea level rise on water resources. WRc Plc. *National Rivers Authority R&D Note* 74. Bristol: National Rivers Authority. (Also published in IWEM Journal, December 1994.)

IPCC (Intergovernmental Panel on Climate Change) (1990). *The IPCC scientific assessment.* Eds. J. T. Houghton, G. J. Jenkins and J. J. Ephraums. Cambridge: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change) (1995a). *Climate change. Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios.* Cambridge: Cambridge University Press for IPCC, 1995.

IPCC (Intergovernmental Panel on Climate Change) (1995b). *IPCC Technical Guidelines for assessing climate change impacts and adaptions.*

Leavesley, G. H. (1994). Modelling the effects of climate change on water resources - a review. *Climatic Change* 28: 159-178.

Parr, T. and A. Eatherall (1994). *Demonstrating climate change impacts in the UK: the DoE Core Model programme.* Published by the Institute of Terrestrial Ecology on behalf of the Department of the Environment. 18 pp.

Author: J A Barker, BGS
T C Atkinson, University of East Anglia

Reviewer: A Eatherall, IH
D Cook, Thames Water Utilities
I H Macdonald, DoE
R Grey, IWEM
P L Younger, University of Newcastle
J M Knowles

DEEP WASTE DISPOSAL

PROBLEM STATUS

The discharge of toxic liquid wastes to underground strata through deep wells, shafts or boreholes is a practice which was once widespread in the UK. In North America, such deep waste disposal has been used extensively in abandoned oil wells and the resulting impacts are well documented (LaMoreaux, 1990). This form of waste disposal effectively bypasses any protection provided by the unsaturated zone.

Potentially adverse effects include groundwater pollution, surface water pollution, ground instability due to subsidence or uplift, sterilisation of mineral and geothermal reserves, induced seismicity, gaseous emissions, and a reduction in the future alternative uses of the underground host formation.

RELATED ISSUES

Climate change
Resource protection and vulnerability
Source protection

TRENDS

Following the introduction of the licensing requirements of the Control of Pollution Act 1974, many relatively small scale operations involving deep well disposal came to light. The majority of these were for the discharge of wastes into disused mineshafts, but a number of instances were identified where toxic waste liquids were injected under pressure into solution cavities in salt mines in the Cheshire basin and Fylde areas (Williams, 1980). This was carried out by the firm mining the salt and the waste was limited to that firm's own waste.

In mineshaft disposal, the wastes are discharged at atmospheric pressures, and in most cases the practise has been carried out for a considerable period. After being issued with a time-limited licence, usually for two years, the operator was required to obtain an environmental impact assessment before the operation could be continued. In the event, most of the operations ceased.

The current situation with regard to the disposal of toxic wastes into salt fields is not known but it probably continues to a limited extent. Operations to stabilise shallow pillar and stall mines by injecting PFA/cement grout, eg in the Dudley area. Walsall Wood is a classic case of mineshaft disposal in UK. A planning application in the late 1970's allowed continuing use of the site but in effect the conditions of the planning consent could not be adhered to and no disposal has continued (both the original borehole and a replacement borehole became blocked).

CONTEXT CHANGES

The need to reduce CO_2 releases into the atmosphere has increased the interest in the deep well disposal of supercritical CO_2 especially into abandoned oil fields and deep saline aquifers. Supercritical CO_2 is a good oil solvent and is immiscible with water and can be used for enhanced oil recovery prior to the reservoir being filled with CO_2.

LEARNING CURVE

There is much information concerning deep well disposal of many types of wastes into many types of formations in North America, but even so there are areas needing continued research.

In the UK, very little has been done except for recent research on the feasibility of the deep disposal of CO_2 from power stations (Holloway and Savage, 1993). This work is currently being undertaken by BGS and British Coal (in association with European partners) with funding from the DTI and the European Commission.

PERSPECTIVES

The disposal of toxic wastes into salt fields is a practice viewed by many, including the DoE, with considerable concern. All deep disposal has the potential to pollute and is only likely to be undertaken in the future when it is seen to be the least damaging environmental option.

BENEFITS AND BENEFICIARIES

Deep waste disposal could be a good means of disposal for several intractable waste streams, eg radioactive wastes presently discharged into surface waters. Research would help identify possible situations where this could be undertaken without detriment to groundwater resources. In particular, salt cavities would be an ideal situation where short lived radionuclides could be stored until their activity decayed to environmentally insignificant levels.

RESPONSE

The response has been to put the onus on the owner to show that deep disposal would not cause environmental problems. This may lead to the abandonment of a deep disposal scheme rather than undertaking an impact assessment.

R & D

- monitor extent of groundwater contamination from selected existing deep waste disposal sites
- develop risk assessment approach to deep waste disposal
- define methods for determining geological suitability for deep waste disposal
- evaluate the effectiveness of containment at existing deep waste disposal sites and if necessary devise improvements.

REFERENCES

Holloway, S. and D. Savage (1993). The potential for aquifer disposal of carbon dioxide in the UK. *Energy Conversion and Management* 34: 925-932.

LaMoreaux, P. E. (1990). Hydrogeology and management of wastes by deep well disposal. In *'A report of the Commission on Hydrogeology of hazardous waste of the International Association of Hydrogeologists'*. Ed. P. E. LaMoreaux and J. Vrba. (International Contributions to Hydrogeology Vol 12). Hannover: Heise.

Williams, G. M. (1981). Underground disposal of wastes in Britain. In *'Proceedings of an International Symposium'*, Noordwijkerhout, The Netherlands, 23-27 March, 1981. Ed: W. van Duijvenbooden, P. Glasbergen and H. van Lelyveld. *Studies in Environmental Science* 17. Amsterdam: Elsevier. pp. 421-426.

Author: G M Williams, BGS

Reviewers: J A Barker, BGS
V G Wilkinson, Walsall Municipal Borough Council
R C Harris, NRA

GEOCHEMICAL BASELINE CHANGE

PROBLEM STATUS

Significant local and regional differences in groundwater quality are found across the UK which are related to the bedrock geology, the extent of water-rock interaction and various geochemical processes. These natural processes provide the characteristic water quality of the UK aquifers. Changes in concentration of major, minor and trace elements may however occur not only between aquifers but within aquifers as water moves along flow gradients. Most groundwaters also contain small concentrations of natural organics which are normally measured in terms of the aggregate parameter, 'dissolved organic carbon' or DOC. The DOC includes low molecular substances such as volatile fatty acids (abundant in groundwater from near oil fields) as well as high molecular weight 'humic' type materials. These have not yet been well characterized in UK aquifers and their change with time is unknown.

Many of these changes are beneficial (eg solution of carbonate minerals during recharge by rainfall, softening of groundwater, denitrification at the onset of reducing conditions). However, there are other changes (eg increase in Fe, F concentrations) which may be undesirable and give rise to problems of concern to water potability and treatment. At individual sites changes in the natural baseline conditions may be induced during prolonged pumping.

An understanding of the baseline conditions is necessary before dealing with pollution since many elements may be present naturally at high concentrations, due to geological anomalies.

RELATED ISSUES

Heavy metals
Land-use change

TRENDS

Several elements (eg Mn, Fe, F, As, Ba) occur naturally in groundwaters at concentrations that may be near to current statutory limits for drinking water. Other elements may occur at concentrations that may be harmful due to deficiencies and require addition to water supplies before distribution (eg F).

In the case of fluoride, non-carbonate aquifers such as the Triassic Sandstone generally do not contain fluoride bearing minerals and the natural concentrations remain similar to those in rainfall throughout the aquifer. In contrast, fluoride is released from fluorapatite and other minerals in carbonate rocks and will quite rapidly reach saturation with respect to fluoride (CaF_2). Where natural softening (base exchange $2Na^+$ - Ca^{2+}) occurs, calcium may then be removed, allowing fluoride to increase in aquifers such as the Chalk and Lincolnshire Limestone.

One of the main controls on element mobility is the redox status of the aquifer. Complete reaction of dissolved oxygen due to its use in the oxidation of dissolved organic carbon, ferrous iron or sulphide minerals, allows the redox potential to fall. In addition to facilitating denitrification, this will allow dissolved iron concentrations to rise.

CONTEXT CHANGES

The natural geochemical conditions in aquifers are the product of processes taking place over a geological time scale under natural head conditions. Any development of the aquifer will disturb the steady state condition, often by speeding up reactions due to increasing supply of reactants. Man made influences, for example acidic deposition, may exacerbate natural changes.

Increase in acidity will accelerate the depletion of base cations in the unsaturated zone and lead to the leaching of trace metals. Areas beneath forested land will be most susceptible. Different aquifers will have different buffering capacities and the effects of changing input acidity are likely to be greatest in sandstones and other base poor rocks. In contrast redox changes are most rapid in aquifers with high concentrations of organic carbon (eg limestones).

The elements/species of greatest concern are those highlighted by the EC (1980) directives on water quality for potable waters and the subsequent UK legislation. Research into groundwater quality (as well as related medical research) is needed to provide up-to-date information that can be used to revise policies on water quality standards.

LEARNING CURVE

In general terms, the geochemical baseline conditions in UK aquifers are quite well known as a result of various studies, some of which are cited below. Of special interest is the occurrence of trace elements and species that are the target of interest in the EC Directives (Pb, Hg, As, Cd etc.). Many of the trace metals are highly toxic and are cumulative poisons.

Whereas the spatial variability of groundwater chemistry is quite well known, more research is needed into the rates of change in natural systems especially the stability of redox zones. An understanding of redox processes and other natural boundaries and barriers in the groundwater system is of fundamental importance in the control not only of natural hazards but also to help regulate the persistence and migration of pollutants. Studies of the behaviour of natural systems enable the basic geochemical principles to be established which can then be applied to systems under stress.

Since many of the changes that affect the groundwater system take place at the soil-bedrock interface and during recharge, transport of chemicals from the soil to the groundwater is an important area of study.

PERSPECTIVES

Although the current level of activity specifically aimed at the baseline geochemical monitoring of groundwater quality is not high, there is increasing international interest in developing a set of key indicator parameters which are sensitive to such changes and that can be used for detecting such changes at an early stage.

BENEFITS AND BENEFICIARIES

The main consumers of the research outlined here are the water companies, but everyone dealing with groundwater protection and the effects of pollution is a potential user since no assessment of human impacts can be made without understanding the natural geochemical background and the geochemical processes controlling this background.

RESPONSE

Considerable interest is shown by individual water companies needing to understand the qualitative stability of individual sources.

There is general interest in the UK community in obtaining a better understanding of the geochemical processes controlling water quality. Water companies are interested in predicting the trends in quality of individual sources.

R & D

- study the natural geochemical processes occurring in aquifers that control migration of harmful elements (both natural and atmospheric)
- improve understanding of the mobility of some key elements (eg As, Pb)
- monitor rate, direction and amount of change under natural conditions near individual sources, eg stability of redox conditional concentrations of related elements
- survey concentration and speciation of naturally occurring organic substances in groundwater.

REFERENCES

Edmunds, W. M., J. M. Cook, W. G. Darling, D. G. Kinniburgh, D. L. Miles, A. H. Bath, M. Morgan-Jones and J. N. Andrews (1987). Baseline geochemical conditions in the Chalk aquifer Berkshire, U.K. A basis for groundwater quality management. *Appl. Geochem.* **2**: 251-274.

Edmunds, W.M., J. M. Cook, D. G. Kinniburgh, D. L. Miles and J. M. Trafford (1989). Trace element occurrence in British groundwaters. *Research Report* **SD/89/3**. Keyworth: British Geological Survey.

Author: W M Edmunds, BGS

Reviewers: D G Kinniburgh, BGS
I Davey, NRA
A R Agg, FWR

HEAVY METALS

PROBLEM STATUS

The term 'Heavy metals' has been defined in many ways but is used here in the sense of potentially toxic trace metals such as cadmium, lead and nickel. It therefore does not include metals such as iron and manganese which though problematic in some groundwaters are neither trace metals nor toxic in small doses. Many 'heavy' metals are highly toxic and act as cumulative poisons or carcinogens in humans. Cadmium and mercury are List I substances and many of the other heavy metals are List II substances.

Where high concentrations of heavy metals occur in groundwater they can be derived either from natural *in situ* sources within the aquifer or from some form of contamination from the surface. For example, shallow groundwaters beneath industrial sites or leaking landfills can be contaminated with heavy metals. High concentrations of heavy metals are not currently a widespread problem in the major UK aquifers although locally they may be of importance.

Since heavy metals are strongly adsorbed by most soils and aquifer materials, especially at neutral to high pHs, high concentrations tend to be found most commonly in acidic groundwaters from sandy or other poorly buffered aquifers. The most common natural source in near neutral groundwaters is from the oxidation and dissolution of the mineral pyrite (FeS_2) which tends to contain high concentrations of a wide range of trace metals and is a common minor mineral in many sediments. Heavy metals may be mobile in near neutral or alkaline groundwaters where they form oxyanions (especially arsenic) or where high concentrations of dissolved organic matter are present. The dissolved organic matter complexes the heavy metal cations to form soluble, and mobile, anionic species.

Groundwater supplies about 30% of the drinking water in the UK and statutory monitoring of drinking water quality shows that, with the exception of iron, manganese, aluminium and lead, contraventions for metals are rare (Department of the Environment, 1993). However, such compliance monitoring does not distinguish between surface and groundwater sources and includes the effects of any blending and pretreatment before distribution. It therefore does not give a very good guide to the heavy metal content of groundwaters *per se* but suggests that problems are unlikely to be widespread.

High lead concentrations may be a problem in some drinking waters but this is because of dissolution from lead pipework and soldered copper pipes not from the groundwater which is invariably low in lead.
Occasionally high heavy metal concentrations are found in the iron-rich sludges produced by iron removal plants at groundwater sources and these sludges may need special disposal.

RELATED ISSUES

Acidification
Acid mine drainage
Contaminated land
Landfill
Source protection

TRENDS

Occasional anomalously high concentrations of heavy metals are found in groundwaters from most UK aquifers. Some of these undoubtedly reflect analytical or sampling errors but others do reflect real and persistent geochemical anomalies.

Since heavy metals are normally strongly adsorbed by soils, soil contamination will tend to give rise to only a small and often imperceptible increase in concentration of heavy metal in the infiltrating groundwater. The amount of heavy metal infiltrating is likely to be strongly dependent on the concentration of dissolved organic carbon which tends to be high in soil but declines rapidly with depth in the deeper unsaturated zone. Once a soil or aquifer is contaminated, this strong adsorption makes clean-up exceedingly difficult and the use of chemical extractants is usually required to remobilize the contaminant.

CONTEXT CHANGES

The slow increase in acidity in many upland pastures may lead to increased concentrations of metals in surface waters and shallow groundwaters. There is currently some concern in the USA and Scandinavia that the continuing acidification of some soils and shallow groundwaters will begin to mobilize some of the lead that has accumulated in soil as a result of the atmospheric fallout from leaded petrol. However, this lead is probably sufficiently tightly bound by most UK soils not to be mobilized to any great extent and so is unlikely to impact significantly on groundwater quality in the UK.

High concentrations of heavy metals may occur naturally, especially in the common accessory mineral pyrite (FeS_2), and in organic-rich sediments. Metals can be released when the pyrite or organic matter oxidizes. Heavy metals can therefore be a problem in acid mine drainage and this is likely to be of greater concern in the future now that many mines have closed. However surface waters are most likely to be affected by this not groundwaters. If heavy metals are released into deep groundwater then they are likely to be subsequently precipitated or sorbed elsewhere within the aquifer.

The 1993 WHO Guidelines for Drinking Water provisionally revised some of the earlier (1984) guideline values for heavy metals. Perhaps the most relevant for groundwaters was the reduction for arsenic from 0.05 mg/L to 0.01 mg/L. Arsenic is sometimes found above this guideline value in UK groundwaters especially in the Chalk. Where present at elevated concentrations, it is normally found as the arsenate ion ($As(V)O_4^{3-}$) which is the dominant form of arsenic in oxidized waters.

LEARNING CURVE

There has been no systematic nationwide survey of heavy metal concentrations in UK groundwaters. The most comprehensive published survey for UK groundwaters is given in the report of Edmunds *et al.* (1989) which covers a range of major and minor aquifers in England and Scotland. Most of the data collection for this survey predated the introduction of the highly sensitive inductively coupled plasma-mass spectrometer (ICP-MS) and so concentrations for many of the heavy metals were below the detection limit. ICP-MS instruments are now installed in many of the major water chemistry laboratories in the UK and these can be expected to lead to an increased understanding of the concentrations and behaviour of trace elements in groundwater.

Reliable baseline data for the major UK aquifers are not yet available for a number of heavy metals (eg mercury, cadmium, lead, arsenic, chromium, antimony and selenium). Because of the difficulty of obtaining reliable heavy metal data for groundwaters, the results are often best put into perspective by comparing with neighbouring samples (the 'local baseline') and by considering the overall geochemical and hydrogeological environment. Sampling and analysis of trace metals in groundwater requires special precautions to minimize sample contamination.

PERSPECTIVES

Heavy metals are not seen as a major problem in the major UK aquifers, but they occasionally give rise to local problems in terms of compliance with drinking water quality standards.

BENEFITS AND BENEFICIARIES

A knowledge of the baseline concentration of heavy metals in UK groundwaters provides a sound basis for interpreting anomalies when they arise. Locally high concentrations of heavy metals in some groundwaters used for public supply are of concern to water utilities.

RESPONSE

Most studies of heavy metals in groundwater tend to take place on an *ad hoc* basis as problems arise. The NRA are in the process of installing a nationwide database management system (WAMS) which should greatly improve their ability to process the trace element data that has been collected and archived and to review it on a national basis. However, it is likely that these data will be far from uniform in terms of geographical coverage and the range of heavy metals available.

R & D

- carry out a survey of arsenic concentrations in susceptible groundwaters and model arsenic speciation and mobility in aquifers
- carry out experimental and theoretical studies of models for heavy metal sorption on aquifer materials in the presence of competing ions at concentrations typical of UK groundwaters
- review recent trace element data in UK groundwaters and update baseline database.

REFERENCES

Department of the Environment (1993). *Drinking Water 1993*. Drinking Water Inspectorate. London: HMSO.

Edmunds, W. M., J. M. Cook, D. G. Kinniburgh, D. L. Miles, and J. M. Trafford (1989). Trace-element occurrence in British groundwaters. *Research Report* SD/89/3. Keyworth, British Geological Survey.

Author: D G Kinniburgh, BGS

Reviewers: W M Edmunds, BGS
S White, Thames Water Utilities

MICROBIOLOGICAL CONTAMINATION

PROBLEM STATUS

The microbiology of groundwater is a comparatively new discipline (Bitton and Gerba, 1984) and has tended to receive less attention in the past than surface water. Populations detected may be indigenous or introduced from the surface but both can influence groundwater quality. Conservative estimates of the survival times of only certain microbes in aquifers are available. If a pathogen can survive a given time period then the transit time must exceed this survival time if the pathogen is not to be detected at the point of abstraction. Abstracted concentrations depend on initial concentrations, survival rates and transit times.

The contamination of subsurface water by pathogenic bacteria and viruses has caused large outbreaks of waterborne diseases. The evaluation of case histories shows that outbreaks have usually happened where the contaminated infiltrating water has effectively bypassed the unsaturated zone (Pekdeger, 1984). Normally the unsaturated zone is a very effective barrier against the infiltration of bacteria and viruses. The main sources of contamination of groundwater are from septic tanks, leaking sewers, sanitary landfills, waste oxidation ponds and the land application of waste water.

In fissured aquifers, microbial transport may be rapid since the microbes may be large enough to be confined to the more rapidly moving fissure water. It has sometimes been noted that microbial contamination of certain boreholes occurs after periods of intense rainfall which is consistent with rapid fissure transport. Recent concern has concentrated on the transport and survival of *Cryptosporidium*, a protozoan pathogen that produces cysts that are resistant to chlorination at water treatment plants.

The microbiological quality of drinking waters is controlled by the EC Directive 80/778 and associated UK regulations. Water intended for human consumption should contain no pathogenic organisms. Maximum admissible concentrations for Total coliforms, faecal coliforms and faecal streptococci are therefore zero which means in this context "not detected in 100 ml samples". Coliforms and streptococci are in this context not pathogenic themselves but indicators of possible faecal contamination by eg *E. coli*. Neither should other pathogens, such as salmonella, entero-viruses, or pathogenic amoeba be present. Guide Levels for the Total viable bacterial count in drinking water are 10/ml at 37°C after 24 hours and 100/ml at 22°C after 72 hours.

Although microbes are responsible for many subsurface reactions that can profoundly affect subsurface water quality (eg denitrification, oxygen depletion, pyrite oxidation, bioremediation etc), these biochemical effects are not considered here.

RELATED ISSUES

Landfill
Remediation
Rising water levels
Sewers, soakaways and septic tanks

TRENDS

The problem areas indicated are likely to increase in significance. Pathogen survival needs to be addressed because of the widespread, and perhaps increasing, application of sewage sludge to land and disposal in landfills.

CONTEXT CHANGES

The implementation of the Urban Waste Water Treatment (UWWT) Directive (91/271/EEC) and the forthcoming cessation of the disposal of sewage sludge to the sea by the end of 1998 is forcing water companies to reconsider their future options for sludge utilization. This includes increasing the already substantial sewage sludge applications to land which may have implications for pathogen levels in groundwaters.

LEARNING CURVE

Microbial populations exist in most geological formations and play a role in certain fundamental geological processes such as diagenesis and mineral formation (Ehrlich, 1990; Chapelle, 1993). These populations can be indigenous, influencing geochemical processes via their nutrient and energy requirements. Populations introduced via boreholes etc will only survive if they are capable of exploiting these same nutrient and energy sources.

The survival of pathogens in groundwaters has been studied and a residence time of 50 days equivalent to a specified horizontal flow-time has been recommended for the prevention of pathogen contamination of groundwater sources (Adams and Foster, 1991). In general, viral persistence is greater in groundwater than in surface waters. However, it is not known what the capacity of an aquifer would be if large and increasing numbers of pathogens were introduced. The aquifer may have a limited capacity to filter out pathogens and complex ecosystems may develop which could support certain opportunistic pathogens.

The transport of microorganisms reflects the interaction of a number of important processes such as physical filtration, adsorption and die off (Pekdeger, 1984). Such transport is also likely to be especially sensitive to the presence of preferential flow paths since die off reduces the effectiveness of the slower flowpaths. Localized infiltration through river channels, beneath septic tanks, leaking sewers or landfills could also be locally significant since the saturated conditions created in these environments bypasses the normal protection provided by the unsaturated zone.

It is generally believed that the matrix of the Chalk aquifer contains relatively small numbers of bacteria since the median pore throat diameter, approximately 0.5 μm, is a little smaller than the size of many bacteria. Under unfavourable conditions, however, the size of individual organisms may reduce. Most of the bacteria in an aquifer are believed to be present in biofilms on the fissure surfaces.

PERSPECTIVES

In the most part, groundwater is considered to be relatively secure from microbiological contamination compared with surface waters but the recent outbreaks of *Cryptosporidium* in groundwater samples have caused a reassessment of this assumption.

BENEFITS AND BENEFICIARIES

Work on pathogen survival and transport in the subsurface would clarify and maybe reduce the recommended 50 day residence time and identify why viruses survive longer than bacteria. This is relatively well known for surface waters but not for groundwater. An understanding of the mechanisms of transport and survival of pathogens such as *Cryptosporidium* would enable appropriate preventative measures to be taken.

Benefiting organisations: NRA, DoE, Water Companies, WSA, HMIP, Local Authorities, and the regulatory agencies in Scotland and N Ireland.

RESPONSE

There has been a limited response in all areas. There is a recommendation for a 50 day residence time for pathogens but such a concept requires some care in application, eg in fissured aquifers. Legislation will require reassessment of this time period.

There have been a number of recent studies financed by the NRA, MAFF, DoE and the Foundation for Water Research on behalf of its members into the origin, fate and treatment of *Cryptosporidium*.

R & D

- improve knowledge of the survival times of exotic microorganisms in aquifers
- carry out and model tracer tests to establish the travel time distribution of various-sized microbes (or their surrogates) in aquifers.

REFERENCES

Adams, B. and S. S. D. Foster (1991). Land surface zoning for groundwater protection. In '*Groundwater pollution and aquifer protection in Europe*', IWEM Annual Symposium 8-9 October 1991, IWEM.

Bitton, G. and C. P. Gerba (1984). *Groundwater Pollution Microbiology*. Chapter 1, pp 1-7. New York: John Wiley and Sons.

Chapelle, F. H. (1993). *Groundwater Microbiology and Geochemistry*. Chapter 7, pp 174-207. New York: John Wiley and Sons.

Ehrlich, H. L. (1990). *Geomicrobiology* (2nd Ed), Chapter 6, pp. 99-130. New York: Marcel Dekker.

Pekdeger, A. (1984). Pathogenic bacteria and viruses in the unsaturated zone. In '*Pollutants in Porous Media*', ed. B. Yaron, G. Dagan and J. Goldschmid. Ecological Studies 47, pp. 195-206. Berlin: Springer-Verlag.

Author: J M West, BGS

Reviewers: P J Chilton, BGS
A Evans, Thames Water Utilities
A R Agg, FWR

QUARRYING

PROBLEM STATUS

Quarrying is one of the largest industries in the UK in volume terms. Some 200 million tonnes of aggregate are required in Britain each year for construction, most of which must be quarried on land. However, quarries do not make good neighbours. They are temporary industrial sites which supply a national need and local benefits but they have a long-term presence. There is increasing public concern over their environmental impact, particularly their visual impact, both during their life and after the extractive phase.

Groundwater encountered in quarry workings causes operational and stability problems for the excavation. Groundwater entry may cause flooding or influence the wall or floor stability. Aquifers intersected may provide persistent and substantial inflows usually from specific geological features. Man-made features (old mineral workings) may even contribute. The water inflows from these features may alter seasonally and create substantial changes to pumping requirements.

Quarrying and other forms of ground excavation can have important and long-term consequences on groundwater. Quarrying generally interferes with local hydrogeology and hydrology. Quarrying material from above a water table removes part of the essential protection for any underlying groundwater reservoir. It also alters the quality and timing and amount of recharge that takes place.

Quarrying material from below the water table results in the physical removal of part of the aquifer and represents a permanent change to the aquifer fabric. Pumping is necessary to permit sub-water table working and to keep deep workings dry. This can have an impact on adjacent springs, boreholes and flows to surface waters especially when aquifer transmissivity is high and workings are deep. Water that is pumped from workings can be dirty and can contaminate both surface water and groundwater resources.

Excavation from below the water table may result in mixing of once separate aquifer waters and this may create unwanted chemical affects due to mixing or to the introduction of suspended solids into the groundwater. Quarrying of certain materials may involve particular water-related problems, eg quarrying in limestone may influence karstic aquifers where groundwater follows specific routes. These situations are difficult to understand and to model realistically (Harrison *et al.*, 1992)

After the extractive phase, when the quarry is allowed to flood back, the quarry void, which has replaced rock of low porosity (say 1%) with 100% effective porosity, means that water level recovery will be slow. Some high level springs may not return and some low level springs may have increased flows.

Chemical changes introduced by oxidation and changed redox conditions during the life of the quarry pit influence the quality of groundwater after flooding and may be persistent (Hester and Harrison, 1994). The material used to backfill quarries, particularly sub-water table quarries will also impact on water quality. It is appreciated that backfilling with waste in aquifers is seldom acceptable.

Pumping to keep mineral workings dry is not subject to licensing as for other groundwater abstraction but a consent is required to discharge abstracted water to surface waters both in terms of quantity and quality. Disposal or storage of the pumped water can pose a problem for operators. The need to pump during winter months when surface water and groundwater levels are naturally high is often greater and the additional discharge may then lead to an increased risk of flooding of rivers and streams.

A good understanding of the hydrogeology and hydrology of potential and operational quarry sites is therefore required by quarry operators for sub-water table operation in order to be able to make informed water management decisions.

RELATED ISSUES

Resource protection and vulnerability

TRENDS

There is a trend towards deeper working in order to minimise the visual impact of quarries. At the same time there is a trend towards a smaller number of larger quarries to meet the increasing demand for stone. The deeper working and the reduction in the number of sites is leading to more sub-water table working and a greater interference with aquifers. It is also influencing the restoration possibilities. Where possible the NRA encourage working of non-aquifer material but this is not always practicable.

CONTEXT CHANGES

The increasing demand for stone and the pressures to go deeper at a smaller number of sites will have greater impact on water resources at a number of sites in the future. Furthermore EC directives on water quality, policies for aquifer protection and groundwater vulnerability classification further limit exploitable water resources and will have an impact on permitted mineral developments. Therefore it is important that the environmental impacts of proposed developments are well understood. Since 1988, an environmental impact assessment has been required for all new mineral workings and extensions.

LEARNING CURVE

It is only since 1988, when an environmental impact assessment became necessary (EC directive 85/337/EEC), that the impact of quarrying and sub-water table working on the environment and on local hydrogeology and hydrology became better appreciated. Exceptions to this include the major quarrying carried out in the Mendip Hills where research began in the 1970's. There is, however, little published evidence (eg Raymond, 1994) from the results of monitoring programmes that show the general effects of mineral workings on groundwater. Each case tends to have site specific features. Different rock types also each pose particular problems. Because this is only a relatively recently studied problem and because of confidentiality, there are, as yet, few published case histories.

Environmental Impact Assessment studies have demonstrated that there is a need to monitor the hydrological and hydrogeological environment locally and regionally over a period of time both before quarry development and during the development. This will enable the temporal variability to be determined and so enable any changes due to the development to be observed. These studies indicate that it is necessary to model the hydrogeology and hydrology in detail. Quarry operators generally require guidelines for suitable monitoring programmes.

Little appears to be known concerning the hydraulic and chemical after-effects and functioning of sub-water table quarry pit voids in aquifers when backfilled or not. Such work is necessary because an understanding of the functioning of the structure in the hydrogeological environment after the life of the quarry pit is necessary if proposals to ameliorate and mitigate possible after-effects are to be effective.

PERSPECTIVES

Studying the hydrological and hydrogeological impacts of quarry workings is important to the Minerals Industry for planning and operation. Mineral Planning presents some of the most confrontational issues and the Department of Environment Minerals Division have a close involvement. The NRA and Environmental Agencies have a stake as guardians of the water environment and Water Companies are stakeholders because their assets could be affected.

BENEFITS AND BENEFICIARIES

The benefits of research into the impacts of quarrying on the hydrological environment are optimum development for the quarry industry with the minimum and managed impacts for the Water Industry and the environment. After completion of the extractive phase, the quarry void, either open or backfilled, should not represent a continuing problem to the Water Industry, having ideally a further use, eg for recreation, amenity, water supply or other community value.

RESPONSE

Quarrying is an essential activity and sub-water table quarrying is likely to increase. The Environmental Impact Assessment procedure ensures due attention is given to the environmental effects of proposed workings but can generate a confrontational presentation of the issues between environmental concerns and the minerals industry. What is required is cooperation and planning with monitoring by interested parties at all steps of the proposed development. The hydrogeology is not always understood and adequate monitoring should be undertaken to enable sound decisions to be made.

R & D

- review the effects of mineral workings on groundwater in the short-term (the life of the quarry) and the long-term (after the extractive phase) including the scale of any likely problems
- document case histories
- produce hydrological and hydrogeological monitoring guidelines in a variety of rock types and environments for quarry operators, especially for sub-water table workings
- evaluate the scale, nature and causes of the vertical and lateral variation in hydrology and hydrogeology of certain rock types eg limestones, to facilitate groundwater modelling and the drawing up of more reliable Environmental Impact Assessments
- review the uses and misuses of abandoned sub-water table quarry voids so as to provide useful guidelines to support Environmental Impact Assessments and restoration plans. In particular, the chemical changes resulting from removal of aquifer material, the mixing of waters from different aquifers and exposure of the aquifers to atmospheric conditions in the quarry void may have long-lasting effects on the hydrogeological regime. These effects are not well understood but may be similar to the persistent chemical changes experienced in abandoned mines (Pentreath, 1994 in Hester and Harrison, 1994).

REFERENCES

Harrison, D. J., D. K. Buckley and R. J. Marks (1992). Limestone Resources and hydrogeology of the Mendip Hills. Report to the Department of Environment. *BGS Technical Report* **WA/92/19**. Keyworth: British Geological Survey.

Hester, R. E. and R. M. Harrison (editors) (1994). *Mining and its Environmental Impact*. Issues in Environmental Science and Technology. Royal Society of Chemistry. 164p.

HMSO (1988). Technical Review of the Stability and hydrogeology of mineral workings. Report to the Department of Environment by Geoffrey Walton and the Department of Mining Engineering, Nottingham University.

HMSO (1991). Environmental effects of surface mineral workings. Report to the Department of

Environment by Roy Waller Associates Ltd. 176p.

Raymond, F. (ed.) (1994). *Mendip limestone quarrying, a conflict of interests*. 70 pp. Somerset Books.

Author: D K Buckley, BGS

Reviewers: I N Gale, BGS
D R C Grey, BGS
S S D Foster, BGS
W Stanton, NRA
A R Agg, FWR

RADIOACTIVE WASTE DISPOSAL

PROBLEM STATUS

In the context of groundwater resources, radioactive waste disposal is a potentially major hazard. Depending upon the half-life and character of the particular radionuclides, the introduction of fairly low concentrations of radioactive waste into groundwaters may render them unusable for urban, agricultural, and probably industrial use for considerable periods of time. Contamination of near-surface groundwaters will also jeopardise existing infrastructure and the environment.

Three type of radioactive waste need to be considered:

1) Low-level waste (LLW) consists mainly of rubbish such as discarded protective clothing and used wrapping material. It comprises around 90% of the total radioactive waste budget and presents only a small risk. Some of this waste is disposed of in the same way as other industrial and domestic waste whereas some is destined to be stored in a more rigorously constructed repository.

2) Intermediate-level waste (ILW) comes from sources such as fuel cladding, reactor components and chemical process residues. It comprises around 10% of the total waste, must be shielded from the environment, and has a long lifespan. This must therefore be disposed of in a repository which will isolate it from the environment for a long period.

3) High-level waste (HLW) only comprises around 0.1% of the total waste but it contains over 95% of the radioactivity. It is mainly the waste resulting from the reprocessing of nuclear fuel. This waste will be stored at the surface either in pond or in a vitrified form until its activity has decayed to the levels of ILW allowing it to be disposed of.

These radioactive wastes may enter groundwater via one of four routes:

(i) Leakage from surface storage sites.
(ii) Spillage during transport.
(iii) Direct introduction into the water cycle through discharge from nuclear power stations.
(iv) Leakage from sub-surface disposal sites.

Leakage from storage sites and spillage are accidental releases and can only be considered for specific cases. In general only a localised region of groundwater will be put at risk as occurred, for example, at Sellafield in the late 1970s. Areas around nuclear power stations must be of primary concern although most of these are coastal so the threat to freshwater resources is limited. In such cases, investigation of the route of the radionuclides into the groundwater and possible remediation measures will be similar to that applied to the studies of underground disposal sites. Different problems need to be considered for two different disposal strategies.

The use of shallow landfill sites for disposal of some LLW only presents the possibility of small amounts of contamination, but the use of a large number of sites spreads the risk over a larger area and some sort of control needs to be maintained. The building of one large repository for ILW is potentially the main source of a major discharge of waste into groundwater and, as such, research into its safety is prevalent. Safety cases for such a site need to demonstrate that waste will be isolated from the biosphere for tens of thousands of years: authorization for disposal will only be granted if annual radiological risk is very small. Since the groundwater circulation is usually the main transport route from the repository to the biosphere, contamination of groundwater resources is included implicitly in such investigations.

RELATED ISSUES

Resource protection and vulnerability

TRENDS

The use of radioactive material anywhere in the UK must be registered and disposal authorised by Her Majesty's Inspectorate of Pollution (HMIP). Around 1000 premises are authorised to dispose of small quantities of radioactive waste including hospitals, universities, nuclear companies and government research and defence bodies. Imposition on operators to observe numerical limits for dosage to the public and to use the best practical means to limit any discharge mean that the trend for risk to groundwater resources is probably downwards.

Discharge to Sea

Radioactivity in liquid wastes discharged into the Irish Sea from the nuclear plant at Sellafield is now only 3% of what it was in 1979. The Thermal Oxide Reprocessing Plant (THORP) which recently came into operation has been designed to contribute only marginally to this.

Shallow disposal of LLW

Small amounts of radioactive waste have been included in landfills around the country. HMIP monitors levels of radioactivity in leachate at these sites and, where appropriate, in local boreholes and streams - recorded levels are very low. Additionally low-level waste (LLW) is presently disposed of in concrete vaults and trenches in glacial sediments at Drigg near the Sellafield site in West Cumbria and in a small site at Dounreay in N. Scotland. Problems and trends associated with this sort of disposal are the same as those for more general landfill, although probably one of the main concerns is keeping a register of what goes where so that potential damage to a large extent of groundwater can be minimised.

Disposal of ILW

The potentially most hazardous and long-lived waste is presently stored at the surface. As far as groundwater resources in the UK are concerned, there are four options for its future disposal:

- (i) Continued storage until a failsafe disposal method is developed.
- (ii) Deep disposal in a low-permeability horizon.
- (iii) Shallow-disposal in a clay-based site or sites.
- (iv) Disposal of the waste outside of the UK, eg seabed disposal or export to an international disposal site.

All of these options have been explored further at some time in the past by the UK government. Storage is not a preferred option as it is considered a greater risk and it is considered that the problem should be dealt with now. Seabed disposal was considered in the early 1980's and then discounted as being of high risk, whereas potential shallow disposal sites were investigated in the mid-1980's before being disregarded in favour of a deep disposal site. This is presently the preferred option with UK Nirex Ltd. being set up by the government and nuclear industry to provide, construct and operate a deep repository. The site under investigation at the moment is 650 m beneath the ground surface at Sellafield where 60% of the waste volume destined for the repository arises (Nirex, 1993). However, should this prove unsuitable then a second site at Dounreay in N. Scotland may come under scrutiny.

Should the repository be sited at Sellafield, it is planned to become operational within the next few decades, although the disposal strategy is constantly under review and deep disposal may lose favour by then. The volume of waste is growing through decommissioning of UK nuclear power stations and operation of THORP although any waste resulting from spent fuel imported for reprocessing is presently returned to the country of origin.

CONTEXT CHANGES

Changes in disposal policy similar to those discussed above could have serious implication. For example, a change of policy towards moving the waste out of the UK would eliminate the problem or, rather, transfer it. A policy of using several shallow disposal sites instead of one deep one could place much larger volumes of groundwater at risk. Changes in the policies of other governments such as Japan and Germany in sending their waste to the UK for reprocessing or in the UK government in accepting the waste will affect the size of the problem.

Events over longer timescales such as environmental changes need to be considered in safety cases for disposal sites anyway because of the long timescales involved. The effects of such changes tend to be specific to sites although sea-level changes could have potentially serious results on the distribution in sediments and groundwaters of radionuclides leaking from shallow disposal sites on the coast.

LEARNING CURVE

Once disposed, waste, either in shallow or deep sites, will tend to be isolated from aquifers by low-permeability media such as clays or crystalline rocks. With regard to the radionuclides returning to the biosphere, the main research will be similar for both disposal strategies and can be broken down into:

(i) Physical containment within the repository or site.
(ii) The breakdown of the waste, release of the radionuclides into solution and the chemical environment within the repository or site.
(iii) The transport of the solution back into the biosphere ie groundwater flow.
(iv) The transport of solutes within the groundwater.
(v) Behaviour of the radionuclide in the biosphere.

Research in connection with the disposal of LLW in landfills is of a generic nature concerned with disposal of any waste in such sites. Most of the research done that is specifically concerned with radioactive waste is in connection with the investigation for a deep repository and covers a large section of the scientific spectrum. Much of the data for this research comes from geological investigation of specific sites and natural analogues and from laboratory and field experiments. Several key issues usually emerge as of paramount importance to the result of performance assessments (eg Chapman, 1994):

(i) Modelling of fracture flow and dual porosity in low-permeability media.
(ii) Gas production through anaerobic corrosion of metals and breakdown of organic waste and its subsequent dissipation.
(iii) Interaction of the near field (the repository and the zone around it on which it has a significant impact) and the far-field (the remaining rock).
(iv) The role of colloids and particulate material in transporting radionuclides.
(v) The role of microbes.

Part of the research involves building up models for such processes. One of the main problems is then to use such models to extrapolate over long timescales and to different conditions. The researcher needs to be able to partially validate such models so that confidence can be demonstrated for predictions and this may be achieved to a degree by using natural analogues, natural geochemical fluxes, and palaeohydrological evidence.

The research itself has led to significant advances in all the fields mentioned above and in particular in areas such as understanding groundwater flow in low-permeability environments and geochemical thermodynamic modelling. However, the understanding of the problems is still developing and as yet no safety case involving the prediction of the behaviour of a deep UK site over the next 10,000 years has been made. This is still the ultimate goal.

BENEFITS AND BENEFICIARIES

All organisations concerned with groundwater flow and chemical transport benefit from the research associated with radioactive waste disposal although the research itself is sponsored almost entirely by the nuclear industry, either directly or through Nirex, and the Department of the Environment. The latter spent £8.2 million on this topic in 1990-91 making it the largest single area in the Department's research programme.

RESPONSE

With regard to the protection of groundwater resources, there is no response to the problem of radioactive waste disposal from organisations outside of the nuclear industry. The shallow disposal sites are not perceived as a problem and any deep ILW disposal site will have to go to public enquiry before construction. It is at this point that the water industry and the Government will presumably raise queries about groundwater protection.

R & D

It is recognized that the R&D needs in relation to deep disposal are currently being addressed by Nirex. The very comprehensive programme of work being carried out could not even be summarized here. The aim here is to indicate the work that is relevant to shallow disposal that has the potential to pollute aquifers on a relatively short time scale.

- A register of LLW disposed in shallow landfill sites needs to be kept. A method of including unauthorised or accidental sources such as old smoke alarms or leaks from storage tanks and laboratories needs to be devised.

- Landfill monitoring for radioactivity.

- Laboratory and field experiments need to be performed to investigate:
  - rate of release from the wasteform.
  - retardation properties of aquifer materials with regard to the commonest radionuclides.
  - the migration pathways from source to biosphere eg fractures, porous media.
  - the dose-response relationship.

- Basic process research into the role of colloids, microbes, dissolved organic material, and contemporary gas generation in transport of radionuclides. All can be expected in disposal sites.

- Modelling - robust models need to be developed that can simulate the laboratory and field data. These can then be used to address the risk to groundwater resources.

REFERENCES

Chapman, N. A. (1994). The geologist's dilemma: predicting the future behaviour of buried radioactive wastes. *Terra Nova* 6: 5-19.

Nirex (1993). Scientific Update 1993. *Nirex Report 525*.

Author: M B Crawford, BGS

Reviewers: J A Barker, BGS
I H MacDonald, DoE
A R Agg, FWR

RADON, RADIUM AND URANIUM IN GROUNDWATER

PROBLEM STATUS

Radon, radium and uranium are naturally-occurring radionuclides which are present in all groundwater (Cowart and Burnett, 1994). Radon, ^{222}Rn, has a half-life of 3.83 d while radium has three isotopes, ^{224}Ra, ^{226}Ra and ^{228}Ra with half-lives of 3.6 d, 1620 a and 5.8 a, respectively. The two longer-lived isotopes of radium are of most concern in groundwater. There are fourteen naturally occurring isotopes of uranium but the natural abundance of ^{238}U is 99.28% and so this isotope and its decay products are of principal concern.

While concentrations in groundwater (where determined) have up to now rarely given rise to concern, there are areas of the UK where rocks such as granite contain relatively high amounts of radioelements which have in the past been implicated as the source of high concentrations of radon gas within dwellings. Recent surveys of radon (^{222}Rn) in dwellings have confirmed that the highest radon concentrations are found in the granitic areas of south-west England with smaller concentrations in parts of the Pennines (associated with phosphatic limestones with high uranium contents) and in granitic areas in Scotland (Institution of Environmental Health Officers, 1988; Wrixon *et al.*, 1988). It is in such areas that the possibility of radioelement concentrations reaching problem levels in groundwater is most likely through the possibility of locally high radioelement concentrations cannot be ruled out elsewhere, for example in limestones where Rn may be produced as a result of Ra and U deposition on fracture coatings and pore surfaces.

Pollution by mine waters could also result in elevated Rn. Thorium, while generally present at lower concentrations than uranium, has a decay product ^{228}Ra which is a beta emitter with a similar radioelement activity to ^{226}Ra. However, data for the ^{226}Ra in UK groundwaters remain sparse and the magnitude of the problem in terms of percentage of land area affected is not at present known in any detail.

RELATED ISSUES

Heavy metals

TRENDS

Being primarily the products of a geological situation, radon, radium and uranium are presumably being introduced into groundwater in a steady-state condition, ie getting no better or worse over time except where pumping and antropogenic pollution affect dissolution, precipitation and mixing of these contaminants. An exception to this generalization is where While no map of radionuclides in groundwater exists for the UK, it seems unlikely that problem concentrations would be encountered outside areas with a high radon gas content, the approximate extents of which are known for the UK (O'Riordan *et al.*, 1987; Miles *et al.*, 1990), though the possibility of transport in solution over considerable distances away from known geological source rocks cannot be ruled out and also concentrations of Rn, Ra and U are not always well correlated with each other.

Additional uranium is added to soils in phosphate fertilizers since these contain enhanced concentrations of U, Ra and Th as natural contaminants. However, this is unlikely to be reflected in significantly increased loads to groundwater.

CONTEXT CHANGES

It is in the nature of the main radionuclide source rocks (generally granites and shales) that they do not form major water supply aquifers although they may provide for a large number of small, unlicensed private water supplies particularly in the south and west of the UK. Therefore any rise in water demand is not likely to result in a major rise in exposure to radon, radium or uranium in these areas. However, some sediments such as the Old Red Sandstone and certain limestones can contain up to 10 mg/L U and may form more important groundwater supplies than the granites or shales. Rises in water demand from such aquifers might therefore have a greater impact.

Future EC directives on radioelement concentrations in drinking water appear unlikely to affect the great majority of groundwater consumers. However, taking the precautionary principle, carcinogens have no thresholds below which there are no adverse effects, and so there will always be a trade-off between the number of probable deaths and cost of supplying water free of these contaminants.

LEARNING CURVE

Most of our knowledge of the deleterious effects of radon, radium and uranium in drinking water comes from research carried out in the USA (summarised in Cothern and Rebers, 1990). In the case of radon, the main danger appears to come from the inhalation of the gas after its release from water, rather than from any direct effects of alpha particle emissions on the gastro-intestinal tract (though this remains the subject of research). As a result, lung cancer is the only disease with epidemiological link to radon exposure. Radium, which is biochemically similar to calcium, concentrates in the bone but is associated with cancers rather than the leukaemias which might be expected from alpha particle impacts on bone. Ingested uranium goes primarily to the bone and kidney. Its effects as a cause of cancer or leukaemia are not well known because its general toxicity to the kidney overrides this aspect.

On the basis of research performed in the USA, the data in Table 1 were calculated to give mean concentrations of radionuclides in groundwater together with lifetime risk. It is clear from Table 1 that radon carries a significantly higher risk than radium, which in turn is associated with a higher risk than uranium. Presumably this also applies in the UK.

Table 1. Mean US groundwater concentrations of radionuclides and associated lifetime risks (from Milvy and Cothern, 1990).

Radionuclide	Mean concentration* pCi/L	Lifetime risk
Radium (^{226}Ra and ^{228}Ra)	1.1	1×10^{-5}
Radon (^{222}Rn)	600	4×10^{-4}

It was calculated by Milvy and Cothern (1990) that a net reduction in health risk could be achieved by relaxing the interim maximum level for uranium set by the US EPA in 1976 (Table 2) provided that the large saving in resources thus achieved could then be devoted to the considerably greater risk posed by radon gas. It seems likely that the emphasis in the UK on the radionuclide hazard posed by radon is therefore an appropriate response.

The WHO guideline for gross alpha activity is currently 0.1 Bq/L (measured after extraction of any radon). If the measurement exceeds this, further examination of the water is required. The WHO guidelines stress that "a value in excess of the guideline value does not of itself imply that the water is unsuitable for consumption" (WHO, 1984). ^{228}Ra is a beta-emitter for which the WHO limit is 1.0 Bq/L and for which the same comment given above applies.

Table 2. Maximum contaminant concentrations in drinking water as set by the 1976 US National Interim Regulations.

Contaminant	Concentration or dose equivalent
Gross alpha	15 pCi/L
^{226}Ra and ^{228}Ra	5 pCi/L
Gross beta	50 pCi/L

PERSPECTIVES

At present the greatest concern about natural radioactivity in groundwater is related to its radon content and the accumulation in confined spaces of radon gas exsolved from groundwater. This has been of concern only locally, for example, in south-west England. However, in order to identify other possible areas of concern or gaps in knowledge, a collation of existing data on all natural radionuclides would be highly desirable.

BENEFITS AND BENEFICIARIES

A better knowledge of the occurrence and concentration of radionuclides (especially but not exclusively of radon) is probably necessary to permit informed decision making and to enable accurate environmental audits to be made. However, any benefits to the health of the nation as a whole are likely to remain relatively small, however well we understand radionuclide distributions.

RESPONSE

To a certain extent the occurrence and problems of the most hazardous radionuclide, radon in the gas phase, have been investigated in the UK by the NRPB and MRC, with constructional aspects being covered by the BRE. However, although the main hazard from dissolved radon is associated with its release to the dwelling-place atmosphere by running taps and showers etc, it is possible that areas with low rock radionuclides but high radionuclide water have escaped notice. To satisfy EC legislation it may have to be positively demonstrated that imposed radionuclide health limits are not being exceeded. While radionuclides in groundwater have been measured as part of hydrogeochemical studies of aquifers, coverage of the UK has not been comprehensive and the existing data remain largely uncollated.

R & D

- review natural radionuclide concentrations using existing groundwater data
- carry out a baseline survey of radon, radium and uranium in sensitive UK aquifers targeting areas where above-average concentrations are expected

REFERENCES

Cothern, C. R. and P. A. Rebers (Eds) (1990). '*Radon, Radium and Uranium in Drinking Water*', Michigan: Lewis Publishers, 286pp.

Cowart, J. B. and W. C. Burnett (1994). The distribution of uranium and thorium decay-series radionuclides in the environment - a review. *J. Environ. Qual.* 23: 651-662.

Institution of Environmental Health Officers (1988). *Radon*. Report of the IEHO survey of radon in homes 1987/8. London: Institution of Environmental Health Officers.

Miles, J. C. H., B. M. R. Green, P. R. Lomas and K. D. Cliff (1990). Radon affected areas: Cornwall and Devon. *Documents of the NRPB*, 1: 37-43

Milvy, P. and C. R. Cothern (1990). Scientific background for the development of regulations for radionuclides in groundwater. In '*Radon, Radium and Uranium in Drinking Water*', ed. C.R. Cothern and P.A. Rebers, Chapter 1, pp. 1-16. Michigan: Lewis Publishers.

O'Riordan, M. C., A. C. James, B. M. R. Green and A. D. Wrixon (1987). Exposure to radon daughters in dwellings. *NRPB-GS6*, Natural Radiological Protection Board. London: HMSO.

Wrixon, A. D. *et al.* (1988). *Natural radiation exposure in UK dwellings*. Report NRPB-R190. Chilton: National Radiological Protection Board.

Author: W G Darling, BGS

Reviewers: B Smith, BGS
W M Edmunds, BGS
D G Kinniburgh, BGS
A R Agg, FWR

RISING WATER LEVELS

PROBLEM STATUS

Groundwater availability contributed to the growth of many of our cities in the late 1800s and early 1900s (eg London, Birmingham, Liverpool, Manchester, Nottingham). Over-abstraction and reduced recharge due to urbanisation resulted in groundwater levels being depressed by several tens of metres. Larger buildings were constructed with deep basements or piles often extending below the original natural groundwater level, as the water level was depressed for many decades to a new dynamic water level. Other underground structures, such as tunnels for underground trains, sewers and water pipes, were also built beneath the natural groundwater level, but above the dynamic level.

Decommissioning of many boreholes during and after the Second World War, together with licensing controls introduced under the 1963 Water Act and deteriorating water quality all contributed to greatly reduced abstraction. Groundwater levels at first stopped falling and then started to rise, due to natural replenishment exceeding this reduced abstraction. In some areas, leakage from water mains and sewers contributed to the aquifer recharge.

Rising groundwater levels may have some beneficial effects, eg where springs, long since dried up, start to flow again. This is the objective of several low-flow alleviation schemes recently implemented where revised abstracting from boreholes aims to ensure that baseflow is maintained at an acceptable level. In the majority of cases, however, there are problems from the effect of increased hydraulic pressures (resulting in changes in geotechnical properties) and water quality on piles and foundations in addition to the flooding of basements and tunnels and the saturation of strata that have been dry for a long time. A particular area of concern is contaminated land and waste-filled sites which, if they become saturated, pose considerable pollution hazards due to the generation and mobilisation of leachate.

Deteriorating water quality is a particular problem related to the oxidation of pyrite in dewatered sediments. Oxidation releases iron and sulphate which is mobilised by the rising groundwater resulting in poor quality or corrosive water. This is particularly severe in coal mining areas where dewatering to facilitate coal extraction has ceased and has resulted in a rapid groundwater level rise and poor quality water issuing at the surface.

RELATED ISSUES

Acid mine drainage
Resource protection and vulnerability

TRENDS

Groundwater levels have been rising in some urban areas (eg London, Liverpool, Birmingham) since the 1950s at rates between 0.3 and 2.5 m/a. Many factors need to be taken into account in predicting future rates of rise and the time when problems will occur. Assumptions have to be made about future trends in abstraction in both urban areas and the surrounding recharge areas. Shallower pumping lifts may result in groundwater abstraction becoming economically attractive again, relative to other sources. The quality of the rising groundwater is an important consideration especially if leakage from sewers provides a significant contribution. Where urban industrial development are located an aquifer recharge areas the potential for pollution from many sources is high. Underground "reservoirs" created by dewatering of aquifers may become attractive sites for artificial recharge (eg north London) which will, at times, enhance the rate of rise of groundwater levels locally. This rise would be controlled during the abstraction phase to avoid additional problems for subsurface structures.

Generally, rising groundwater levels have not been controlled by resumption of pumping to exploit the resource as the quality is often poor, particularly if the rise is partly due to leaking sewers. In most cases groundwater levels have had to be controlled by increased pumping to waste to keep tunnels (eg British Rail in Liverpool) and basements dry.

CONTEXT CHANGES

As groundwater levels rise and approach underground structures, the most cost-effective solution appears to be controlled pumping to stabilise groundwater levels at an acceptable level. Depending on demand for water and the quality of the groundwater this can be regarded as either a resource or a disposal problem. Additionally, higher groundwater levels reduce pumping costs and, depending on the cost of alternative sources, groundwater may become the most economic source of water. Existing under-utilised abstraction licences could result in groundwater levels falling again if full entitlements were to be taken up once more.

LEARNING CURVE

The problem has been appreciated for several years and its significance has been quantified by monitoring rates of rise in many locations. Groundwater quality problems due to saline intrusion, leakage from overlying argillaceous formations, oxidation of iron pyrites in coal-bearing rocks and arenaceous deposits (eg Basal Sands in the London Basin) and mobilisation of palaeowaters are understood in general but need to be quantified in each case. Water quality degradation by polluted recharge water from leaking sewers and industrial activity has been studied in several areas but further work is needed to assess the scale of the problem and the fate of pollutants in both the saturated and unsaturated zones of aquifers. The assessment of recharge in urban areas is difficult to quantify because natural recharge may be reduced by roof and paved area drainage, but recharge of water from sewers and water mains may outweigh this reduction. The permeability of near-surface rocks will determine whether leakage finds its way to surface drains or to the water table where it will increase the rate of groundwater level rise.

PERSPECTIVES

Institutions, companies and private individuals affected or threatened by rising groundwater levels will perceive the problem. However, the responsibility for managing the levels is not clear cut and may be the subject of discussion or litigation. Water companies are often the most suitable organisations to undertake pumping to control groundwater levels. However, they will require reimbursement for pumping and discharge of this water and close liaison with the NRA and other beneficiaries is needed. In some cases water supply companies may perceive rising groundwater levels to be an asset that can be economically exploited. Dependent on the quality of the water, utilisation should be encouraged rather than pumping to waste.

BENEFITS AND BENEFICIARIES

An understanding of the rates of rise of groundwater, preferably using a predictive model, together with predictions of likely physical and chemical impacts is vital for organisations and individuals affected by the rise to enable them to make informed decisions on how best to mitigate the effects. Benefits from this knowledge include the ability to plan cost-effective strategies to contain the problem. If predictions are made several years before impacts are felt then solutions can be planned and all beneficiaries can be fully involved. This is preferable to one organisation having to deal with the problem in an *ad hoc* manner when the impacts start to be felt.

Beneficiaries of research into the problem include the NRA who are responsible for managing groundwater resources and dealing with problems that may arise from the resurgence of springs and seeps of poor quality groundwater. Water companies could benefit from a resource becoming economically exploitable again. Many other organisations including owners of underground railways and property and municipal councils would also be potential beneficiaries of research that would enable prediction of the impacts of rising groundwater levels.

RESPONSE

Studies have been undertaken to evaluate the rates of rise and likely impacts of rising groundwater under several major cities, most notably, London, Liverpool and Birmingham. These studies have resulted in a better understanding of the problems and recommendations for both temporary and longer-term solutions. In Liverpool, the underground railway acts as a sump to rising groundwater and this is removed by increased pumping to waste because of the poor quality of the water. In other cities where the groundwater is of acceptable quality, it has the potential to be used for supply.

R & D

- develop predictive models for defining which areas will be affected first and when

- assess the acceptability of the impacts of resaturated strata on the chemical and physical stability of built structures
- investigate legislative and institutional framework for dealing with rising groundwater levels
- develop innovative pumping/drainage schemes and utilisation of water
- investigate the impact of leaks from mains on rising groundwater levels and assess the cost/benefit of reducing this leakage.

REFERENCES

Brassington, F. C. and K. R. Rushton (1987). A rising water table in central Liverpool. *Quart. J. Eng. Geol.*, **20**: 151-8.

Knipe, C. V., J. W. Lloyd, D. N. Lerner and R. Greswell (1993). Rising groundwater levels in Birmingham and engineering implications. CIRIA Special Publication 92, London.

Lucas, H. C. and V. K. Robinson (1995). Modelling of rising groundwater levels in the Chalk Aquifer of the London Basin. *Quart. J. Eng. Geol.* (in press).

Marsh, T. J. and P. A. Davies (1983). The decline and partial recovery of groundwater levels below London. *Proc. Instn Civ. Engrs. Part 1*, **74**: 263-76.

Price, M. and D. W. Reed (1989). The influence of mains leakage and urban drainage on groundwater levels beneath conurbations in the UK. *Proc. Instn Civ. Engrs*, Part 1., **86**: 31-9.

Simpson, B., T. Blower, R. N. Craig and W. B. Wilkinson (1989). *The engineering implication of rising groundwater levels in the deep aquifer beneath London*. CIRIA Special publication 69, London: The Construction Industry Research and Information Association.

Wilkinson, W. B. and F. C. Brassington (1991). Rising groundwater levels - an international problem. In *'Applied Groundwater Hydrology'*, pp. 35-53. Oxford: Oxford University Press.

Author: I N Gale, BGS

Reviewers: N S Robins, BGS
D R C Grey, BGS
A R Agg, FWR
M Owen, NRA
M Price, Reading University
R Sage, Thames Water Ltd
P Aldous, Thames Water Ltd

SALINE INTRUSION

PROBLEM STATUS

Saline intrusion is generally considered to be due to a landward movement of the saline interface that exists where coastal aquifers discharge to the sea or tidal estuaries. Inland aquifers remote from the coast may also suffer water quality deterioration by mobilisation of saline waters of diverse origin within the aquifer, in response to pumping. In coastal regions the boundary between the discharging fresh groundwater and seawater is usually thought to be wedge-shaped and located at an equilibrium position governed by the balance between the seaward flux of freshwater and the tendency for seawater to move inland. At the interface, diffusion and dispersion processes, aided by tidal fluctuations expand the contact into a transition zone of mixed water which can be wide, and is part dependent on aquifer properties. The interface position changes laterally and vertically in response to the net seaward flux of fresh groundwater, which is in turn influenced by seasonal changes in water level, hydraulic gradient and abstraction, and in the longer term, by changes in sea-level and freshwater recharge.

In practice the saline interface can be irregular with more inland boreholes sometimes affected sooner. Saline intrusion effectively limits the quantity of groundwater that can be abstracted due to deterioration in quality unless a positive seaward flow of groundwater is maintained. The problems with salinity are potentially large yet relatively little information is available on this topic.

The anticipated sea-level rise over the next century due to global warming will exacerbate saline intrusion (eg Warwick and Oerlemans, 1990; WRc, 1992).

Coastal aquifers are close to the end of regional flow systems and as such may contain saline waters due to prolonged water-rock interaction. Increased freshwater abstraction from coastal aquifers may mobilise unwanted saline waters.

Two types of intrusion are recognised. *Passive* saline intrusion is a natural process in which positive seaward hydraulic gradients are maintained. The interface responds very slowly (10-100 years) to changes in flux. *Active* saline intrusion occurs when water levels are lowered by pumping and the natural hydraulic gradients are reversed. There is then inland movement of the interface (which stabilizes on a time scale which can vary from weeks to years) and continues to the lowest point of the hydraulic gradient, towards the centre of pumping. Intrusion effects may occur at depth in the aquifer, at the coastal margin, or they may occur at a shallow level from estuarine-borne saline water. They can be experienced some considerable distance inland from the coast.

Active saline intrusion of important regional aquifers occurs in Chalk on Humberside, around Ipswich, along the Thames Estuary, and on the south coast and in triassic sandstones on Merseyside. Local aquifers at risk include the Crag in East Anglia. It places a limit on the quantity of freshwater that can be abstracted in those coastal regions.

RELATED ISSUES

Afforestation
Resource protection and vulnerability

TRENDS

The coastal region is increasingly recognised as a line of natural defence against the sea with the environment in a coastal dynamic state. Coastal regions are areas of increasing population, industry and agriculture and have growing seasonal water demands due to tourism. These all result in increasing demands for water supply. In some industrial coastal regions eg Merseyside, the London area, reduced industrial abstraction is causing rising groundwater levels.

Intrusion changes are continuous and long-term and are linked to environmental and climate changes.

Some predictions indicate a rise in sea level due to global warming of 0.3 to 1.1 m over the next 100 years. If this becomes reality it will have a major impact on coastal aquifers and estuarine borne saline intrusion.

CONTEXT CHANGES

There is an increasing general awareness of the important of the coastal region as a special environment in a constant dynamic state. It is currently the focus of a community research programme (the NERC LOIS Project) which recognises it importance as a national resource.

LEARNING CURVE

The basic theory of freshwater/saltwater dynamics is well understood and current models are quite effective for relatively homogeneous aquifers on a regional scale.

The actual effects in real aquifers are in contrast poorly understood. Observations in Chalk boreholes over 5 years on the South Coast (Southern Science, 1992) showed unique and unpredictable salinity changes; boreholes more remote from the sea affected more strongly and earlier and several anomalous responses. Complex changes in salinity are documented in some Triassic Sandstone boreholes.

Past research, principally in the Chalk, has identified areas of active saline intrusion and models have been constructed to manage groundwater abstraction. Southern Water has successfully operated a system of coastal and inland boreholes (leakage and storage stations) in the Brighton area to optimise the interception of throughflow and control the extent of intrusion (Monkhouse and Fleet, 1975; Headworth and Fox, 1986; Southern Science, 1992).

Birmingham University have done much work on Humberside, both south and north of the Humber, and constructed numerical models to predict the effects of abstraction on the position of the interface (University of Birmingham, 1978, 1985). The current level of saline intrusion on the Suffolk/Essex coastline is unclear, as is the rate of propagation and drainage in coastal marsh areas can influence both surface water and groundwater salinity distribution (Holman, 1994).

PERSPECTIVES

The NRA have a role in monitoring and protecting water quality which may be affected by saline intrusion.

BENEFITS AND BENEFICIARIES

The direct benefit of research into saline intrusion is improved abstraction policies and water management for Water Companies, NRA and ultimately consumers. Brackish water from the mixing zone may be an exploitable resource given suitable treatment and a better understanding of controls on salinity. Improved understanding of saline intrusion in coastal marsh areas will aid conservation bodies, eg English Nature, in managing coastal wetland environments.

RESPONSE

Current management options in the Yorkshire region are that the Hull area Chalk aquifer up to the 40 Northing has been designated as a fully developed zone and no more abstraction licences are being granted except for a few minor abstractions. The baseline of the control curves which define storage the amount of available storage in the aquifer was defined by the level reached in the 1976 drought. Above that, abstraction is allocated on the basis of the available storage.

R & D

- establish the best practice for monitoring the extent of saline intrusion
- evaluate if there are differences between salinity changes observed in boreholes and piezometers compared with changes taking place in the aquifer
- evaluate the value of boreholes and piezometers for monitoring changes in salinity as opposed to sealed *in situ* transducers or time-series geophysical surveying.
- determine the physical features which control general fluid movement in the rock mass
- explore the use of saline water bodies as repositories for fresh water storage
- examine if and how aquifers can recover from short term saline intrusion
- review whether present operational strategies for coastal aquifer abstraction is sensible or overly-cautious

- examine the discharge mechanisms of confined coastal aquifers, and the water and solute balances of the coastal region in general.

- monitor saline intrusion even where there is currently no perceived problem in order to provide the database of information needed for future understanding and management

- develop models so as to better handle the special combination of flow, dispersion and geochemical processes that occur in the coastal region especially for the dual-porosity Chalk aquifer.

REFERENCES

Foster, S. S. D., E. L. Parry and P. J. Chilton (1974). Groundwater Resources Development and Saline Water Intrusion in the Chalk Aquifer of North Humberside. *Hydrogeology Technical Report* **WD/74/4**. London: Institute of Geological Sciences.

Headworth, H. G. and G. B. Fox (1986). The South Downs Chalk aquifer: its development and management. *J. Inst. Wat. Eng. & Scientists* **40**(4): 345-361.

Holman, I.P. 1994. Controls on saline intrusion in the crag aquifer of north-east Norfolk. Ph.D. Thesis, Univ. of East Anglia, Norwich 265 pp.

Monkhouse, R. A. and M. Fleet (1975). A geophysical investigation of saline water in the Chalk of the south coast of England. *Quart. Jour. Eng. Geol.* **8**: 291.

Rushton, K. R. (1980). Differing positions of saline interfaces in aquifers and observation boreholes. *J. Hydrol.* **48**: 185-189.

Southern Science (1992). Saline Monitoring Programme: A Review of Work in the Sussex and Dover/Deal Regions since 1985 and Recommendations for Future Work. Report **92/6/299**. Worthing: Southern Science.

University of Birmingham (1978). South Humberside Salinity Research Project. Report to Anglian Water Authority.

University of Birmingham (1985). Yorkshire Chalk Groundwater Model Study. Final Report.

Warwick, R. A. and J. Oerlemans (1990). 'Sea level rise'. In: *Climate Change: the IPCC scientific assessment*, eds J. T. Houghton, G. J. Jenkins and J. J. Ephraums. Cambridge: Cambridge University Press.

WRc (1992). Effect of sea level rise on water resources. *NRA Project 277, Note 74.* Bristol: National Rivers Authority.

Author: D K Buckley, BGS

Reviewers: J A Barker, BGS
D S Chadha, NRA
I H MacDonald, DoE
P J Shaw, NRA
J W Lloyd, University of Birmingham
A R Agg, FWR
K Hiscock, University of East Anglia

SEWERS, SOAKAWAYS AND SEPTIC TANKS

PROBLEM STATUS

Domestic sewage has the potential to pollute both groundwater and surface water. Sewage contamination of water supplies is well documented in the developing world, but problems also occur in the developed world from leaking sewers, soakaways and septic tanks. The majority of UK household, commercial and industrial premises are connected to mains sewerage, although septic tanks are still common in rural areas. This paper focuses predominately on the problem from leaking sewers.

The main problem associated with leaking sewers is the potential bacteriological contamination of public water supply boreholes. Where such contamination affects a private non-chlorinated source or a public water supply borehole where chlorination has broken down, the effects on public health may be dramatic. For example, at Bramham in Yorkshire in 1980, a leaking sewer contaminated a public water supply borehole where chlorination had broken down (Short, 1988). This resulted in widespread public health problems, with some 3,000 cases of gastroenteritis recorded. A similar incident occurred at Naas in Ireland in 1991 (Garrett, 1992).

In addition to bacteria, sewage can contaminate groundwater with a variety of other determinands reflecting the nature of activities in the catchment of the sewerage system. While bacterial pollution is unlikely to threaten the long-term sustainability of groundwater resources because of the rapid die-off of bacteria in the subsurface, some of the other possible contaminants are much more persistent and may pose longer-term problems. Domestic sewage may contaminate groundwater with nitrogen species (nitrate and ammonia), sulphate, chloride, phosphate and potassium, and any of these may be indicators of contamination from sewers. High concentrations of dissolved organic carbon and boron may also indicate such pollution. Industrial sewage effluent may contain additional potential contaminants, such as chlorinated solvents and heavy metals (Burston *et al.*, 1993). Many of these latter determinands are List I substances (as defined by the EC Groundwater Directive 80/68/EEC) which are prohibited from being discharged to groundwater. There is also widespread evidence of deterioration in urban groundwater quality, where sewer leakage is likely be partly responsible (Halliday and Lerner, 1992).

Septic tanks as a means of sewage disposal are generally found in sparsely populated rural areas. Poor effluent distribution or overloading of the system can result in groundwater contamination. Septic tanks are the most frequently reported source of groundwater contamination in the USA, probably reflecting their more widespread use and the importance of shallow aquifers. In Ireland, septic tanks are also one of the major sources of groundwater pollution. This is often due to poor siting over vulnerable fissured aquifers with effluent disposed of by soakaways rather than the more appropriate field drainage systems.

In the UK, there is no evidence that septic tanks pose a widespread risk to groundwater resources. However, significant localised contamination may occur in remoter parts of the UK, but little groundwater monitoring is likely in these areas.

There is also concern about the drainage of highways, railways, airfields and other large paved areas to groundwater by soakaways. Such systems may provide greatly reduced protection of groundwater from pollutants, as they are excavated to provide a rapid route to the water table. Pollutant transport may be further enhanced by fissure flow in the unsaturated zone. The most common pollutants are likely to be fuels, oils, defoliants and deicing chemicals. Instances of quality deterioration at public supply sources may have been facilitated in some cases by rapid soakaway drainage reducing the potential for pollutant attenuation by adsorption and degradation.

RELATED ISSUES

Contaminated land
Resource protection and vulnerability
Source protection
Unregulated rural supplies

TRENDS

There is insufficient data to determine whether sewage-related groundwater contamination is getting better or worse. The list of documented incidents of sewer leakage is relatively short, equating to approximately one incident per water service company area every seven years. However, some qualitative assessments may be made:

(i) Chlorination of public water sources means that sewage-related groundwater pollution generally has had less impact this century than last.

(ii) The deterioration of old (frequently Victorian) sewers in major urban areas (such as Liverpool and Birmingham) means that sewer leakage is likely to increase, contributing to deterioration in urban groundwater quality, unless rehabilitation is undertaken. More modern sewers have been constructed to higher performance specifications and are less likely to give rise to problems in the future.

CONTEXT CHANGES

Attention has been focused on leaking sewers through the NRA's *Policy and Practice for the Protection of Groundwater* published in 1992. The document includes the construction of foul sewers in a list of unacceptable activities in the inner source protection zone immediately adjacent to a groundwater source, and the onus is placed on developers, sewerage undertakers and their consultants to demonstrate that any proposed activity does not put groundwater resources at risk. Developers and sewerage undertakers will therefore be required to give groundwater protection issues a higher priority in future during sewer construction.

LEARNING CURVE

A CIRIA funded study is presently being concluded which has examined the occurrence, nature and causes of sewer-related groundwater contamination in England and Wales (Misstear *et al.*, 1996). The results of the study are as yet unpublished, but the major findings can be summarised as:

(i) An extensive literature survey identified 18 incidents of sewer-related groundwater contamination in England and Wales, dating from 1928.

(ii) A questionnaire survey directed at the water industry identified a further 42 incidents.

(iii) The incidents identified did not generally lead to any ill-effects on public health, owing to the general chlorination of water supplies (the exception being the Bramham incident detailed above).

(iv) The generally poor quality of many urban groundwaters suggests leaking sewers are a contributory factor.

(v) The best determinands for defining sewage-related groundwater contamination are considered to be bacteria, nitrate, phosphate and boron.

(vi) Existing groundwater monitoring is generally inadequate both in terms of geographical coverage and relevant indicator parameters to quantify the scale of sewage-related groundwater contamination. There is little monitoring in urban areas from which sewage-related groundwater pollution could be detected and very little monitoring of private water supplies in rural areas to indicate pollution originating from septic tanks.

Although the research described above has improved the understanding of the extent and nature of sewage-related groundwater contamination in England and Wales, the key processes involved in sewer failure are still relatively poorly understood and further research is needed here. Additionally, the pollutants frequently released into groundwater from sewage (such as bacteria and nitrate) often have other sources, with the result that in urban areas particularly, the contribution to groundwater quality degradation from sewer leakage cannot be quantified. More research is required into specialised analytical methods, such as the use of nitrogen isotopes.

PERSPECTIVES

The regulators are aware of the issue of leaking sewers, as shown by the NRA's policy statements related to sewers in the National Policy and Practice for the Protection of Groundwater. Water utilities are also well aware of the issue, as evidenced by their funding of the CIRIA project. However, it is likely that more information is required on the scale of the problem before they would consider adopting costly measures to deal with sewer leakages by assessing (a) the lengths of sewers within Inner Source Protection zones in England and Wales, and (b) the costs of investigating and remediating leaking sewers.

The perspective of developers is likely to be focused on any increased costs of a) constructing new sewers to higher specifications or b) maintenance of existing sewers in areas where groundwater is vulnerable. In the construction industry, many pipe manufacturers do not consider that groundwater pollution from sewers is an issue at all.

Regarding septic tanks and soakaways there is much less perception of a groundwater pollution risk both by the regulators and others, presumably based partly on the current lack of evidence from the albeit limited monitoring.

BENEFITS AND BENEFICIARIES

All organisations concerned with groundwater quality benefit from research into leaking sewers and septic tanks. Such organisations are mainly in the water industry, for example the NRA, water service companies and water utilities.

RESPONSE

The NRA have taken an active stance on the presence of sewage works, foul sewers and storm overflows within source protection zones, as defined in Appendix H of their Aquifer Protection Policy. The laying of new main sewerage systems within Zone I (the inner source protection zone) is classified as an unacceptable activity, although the NRA state that the use of pipework less vulnerable to leakage would be considered on a case by case basis.

Various research projects on groundwater pollution by sewers and related urban groundwater quality have been conducted by the Hydrogeology Research Group at the University of Birmingham.

The CIRIA research project discussed earlier in this paper (Misstear *et al*) is now also complete, and will probably be published in early 1996.

A three year research project into groundwater quality in Nottingham including the role of leaking sewers is currently being undertaken in the Department of Civil and Environmental Engineering at the University of Bradford.

R & D

Field studies of specific pollution incidents including:

- detailed hydrochemical studies using nitrogen species, boron and phosphate as potential tracers of leakage from sewers

- nitrogen isotope studies to identify the source of high nitrate groundwaters.

REFERENCES

Burston, M. W., M. M. Nazari, P. K. Bishop and D. N. Lerner (1993). Pollution of groundwater in the Coventry region (UK) by chlorinated hydrocarbon solvents. *J. Hydrol.* **149**: 137-161.

Garrett, P.G. (1992). Calling for the doctor at Kildare. *Water Bulletin* **494**: 6-7.

Halliday, D. and D. N. Lerner (1992). Sewers as a source of groundwater pollution in urban areas. *Unpublished Report, Hydrogeology Research Report, University of Birmingham.*

Lerner, D. and D. Hoffman (1993). From leaky sewers to groundwater pollution. *Water and Waste Treat.* **36**: 32-33.

Misstear, B. D., M. E. D. White, P. K. Bishop and G. Anderson (1996). Reliability of sewers in environmentally sensitive areas. *CIRIA Research Report 488* (in preparation).

Price, M., T. C. Atkinson, D. Wheeler, J. A. Barker and R. A. Monkhouse (1989). Highway drainage to the Chalk aquifer: the movement of groundwater in the Chalk near Bricket Wood, Hertfordshire, and its possible pollution by drainage from the M25 motorway. *BGS Technical Report* **WD/89/3**. Keyworth: British Geological Survey.

Short, C. S. (1988). The Bramham incident, 1980 - an outbreak of water-borne infection. *JIWEM* **2**, 383-390.

Authors: P Bishop, Mott MacDonald
J Chilton, BGS

Reviewers: B D R Misstear, Trinity College, Dublin
A R Lawrence, BGS

SLUDGE UTILIZATION

PROBLEM STATUS

'Sludge utilization' is used here to refer to all forms of organic waste which may be applied to farmland. Organic wastes are applied to land in the form of farm wastes (slurry, farmyard manure, etc) and sewage sludge. The quantities involved are large. In the UK, the total amount of farm waste produced is equivalent to about 150 million people. This is necessarily disposed of close to the source of production, ie in the animal rearing parts of the country. Some 42% of UK sewage sludge is also applied to the land with about 1% of the UK's farmland receiving sewage sludge, somewhat less in any one year. As a result of recent EC legislation requiring the cessation of dumping of sewage sludge to sea by December 1998, there are likely to be significant increases in the amount of sewage sludge applied to land in the future. Also in response to the Urban Waste Water Treatment Directive, it is expected that sewage sludge production will increase by 50% by the year 2006. The application of sewage sludge to land is strictly regulated and is subject to a Code of Practice (Department of the Environment, 1989).

The impact of sludge applications on groundwater will probably be focused on the amount of nitrate leaching and the fate of any persistent trace organics derived from sewage sludge. The potential for nitrate loss from organic manures is greater than from inorganic fertilizers because of difficulties in making timely, accurate applications of readily available nitrogen. These manures are often applied to arable stubble and grassland throughout the autumn and winter as and when convenient and soil conditions permit, or at rates well in excess of crop uptake. Substantial nitrate leaching is likely to result (MAFF, 1993a). In the past, high application rates of sewage sludge at dedicated sites may have also led to high rates of nitrate leaching to groundwater.

The impact of the heavy metals and pathogens contained in sewage sludge is not dealt with in detail here since this is largely a matter of soil protection. Pathogen levels are substantially reduced on treatment, the reduction depending on the type of treatment.

The utilization of sludge is a complex issue because it is closely tied to a wide range of interrelated issues involving agriculture, industry (including the water industry), forestry, energy and the environment. The final outcome is likely to be strongly influenced by national and EC legislation to protect the environment as well as the prevailing economics of the various options for utilization and disposal.

RELATED ISSUES

Microbiological contamination
Nitrate

TRENDS

Changes in the amount and type of organic farm wastes produced will mainly reflect changes in the number of farm animals. As far as groundwater is concerned, it is the application of sludges to areas overlying aquifers that is critical. All of the sludge derived from farming is recycled to the land as well as about 40% of the UK annual sewage sludge production. This will remain the principal outlet in the future with possibly twice the quantity of sewage sludge being recycled in this way by 2006 (Hall, 1993).

The increasing use of secondary digestion of sewage sludges will increase the uniformity of sewage sludge and therefore make it more suitable as a N fertilizer.

CONTEXT CHANGES

The application of farm animal wastes to land is currently under scrutiny and is subject to a wide range of statutory and non-statutory regulations and recommendations (Parkinson, 1993). As a result of recent EC legislation requiring the cessation of dumping of sewage sludge to sea by December 1998, there could be significant increases in the amount of sludge applied to land. The cost of landfill is expected to rise as the demand increases and as stricter controls are enforced. A landfill levy is also being introduced. There is likely to be pressure to reduce the amount of biodegradable organic matter that is landfilled (to reduce methane emissions). Even when sludge is incinerated, most of the heavy metals will be retained in the ash and eventually landfilled. Incineration is also subject to planning permission and tight air quality standards are likely to be imposed.

Sludge application to land has beneficial effects arising from the organic and nutrient contents of the sludge and can usefully be used not only in agriculture but also in land reclamation and forestry. Some water utilities are looking at combining sewage sludge application with energy forestry (short rotation coppicing of poplar and willow) as well as with traditional forestry. The possible negative impact on groundwater is that nitrate leaching from large or uneven applications of sludge could be significant. However, large applications are unlikely in the future as farmers and others respond to recommendations (MAFF, 1991) and legislation (Parkinson, 1993).

The timing and size of all types of sludge applications will be restricted in the proposed Nitrate Vulnerable Zones (NVZs) - a maximum of 210 kg N/ha/a can be applied and only at non-sensitive times. These regulations aim to limit the negative impacts on groundwater.

LEARNING CURVE

The quantity of excreta produced from livestock and its N content vary widely with class of stock, diet and water intake, building design and environment. Using average values of excreta output per animal, together with typical N contents and livestock census data, it has been estimated that the annual output of N by housed livestock (in millions of tonnes of N) are: cattle (0.32), pigs (0.08) and poultry (0.11) (MAFF, 1993a). The N contained in these manures is approximately equivalent to 30% of the 1.5 million tonnes of N in chemical fertilizers used in 1991. However, nationally the distribution is uneven and reflects variations in livestock density.

Treatment of sewage yields a range of different types of sludge which vary in physical consistency and N content. Currently about 30 million wet tonnes of sewage sludge are produced each year, 42% of which is applied to agricultural land. This contains about 15,000 tonnes of N (MAFF, 1993a). Sewage sludge applications are currently controlled by the Sludge (Use in Agriculture) Regulations 1989 which enforce the EC Sludge Directive 86/278/EEC.

There is little evidence and little likelihood that heavy metals from sewage sludge will be mobile enough to affect deep groundwater since they tend to be strongly bound by soils and aquifers. Generally, heavy metals are least strongly bound, and therefore most mobile, under acid conditions (pH less than 5.5). Such conditions are rare in the major British aquifers which are dominated by well-buffered groundwaters with a pH in the range 6.5-8.5. Existing legislation controls application of sewage sludge by setting limits for the concentrations of heavy metals in soils. The Bradshaw Committee (MAFF, 1993b) has recently reviewed the current limits for sewage sludge application to land and has expressed some concern about the potentially deleterious effects on rhizobia (a type of nitrogen-fixing microorganism associated with legumes) due to zinc and to a lesser extent, cadmium, at soil metal concentrations close to and sometimes below the 1989 UK limits. The solubility of heavy metals in soils, their plant availability and toxicity is strongly pH-dependent and so the maximum limits vary with the pH of the soil.

While the solubility of most potentially toxic elements decreases with increasing pH, those elements that form strong anionic species (selenium, arsenic, molybdenum and chromium) may increase in solubility with increasing pH and therefore will be able to travel more readily through soils and aquifers at the near neutral pH's typical of them.

Recently there has been some concern about the quantities of volatile organic compounds (VOCs) that could be applied to land in sewage sludge and which could potentially contaminate groundwater. Aromatic VOCs such as toluene are common VOCs in sewage sludges. Concentrations are not generally thought to give rise to a serious threat to groundwater although specific sludges with particularly high concentrations would best not be applied to soil. The leaching of persistent trace organics to groundwater also needs to be monitored.

There is little information on the rate of degradation of VOCs and other trace organics in UK aquifers. The rate is likely to depend on many factors including the availability of other organic carbon substrates, the redox status of the groundwater and the presence and activity of the microorganisms which can degrade these compounds. This is a difficult area to study. The rate of degradation in aquifers is likely to be much smaller than in soils, for which most data are available (Jones and Wild, 1991), perhaps by orders of magnitude, but could still be significant because of the long timescales involved in groundwater circulation.

PERSPECTIVES

The controls on the disposal of sludge to land have been imposed to ensure that the long term viability of soil for agricultural use is maintained and that the quality of surface and groundwater is not significantly reduced.

BENEFITS AND BENEFICIARIES

Sludge can be both an asset and liability. Both agriculture and the water industry have a continuing and growing problem in disposing of sludge within the constraints of a wide range of guidelines and regulations and an increasingly environmentally-aware population. Agriculture and forestry can benefit from sludge applications providing they meet the appropriate environmental quality standards. Increased recycling of the nutrients continued in sludges is of benefit to all.

RESPONSE

There has been an increasing awareness in recent years of the potential of significant nitrate leaching from the applications of farm wastes to agricultural land. This has led to various codes of 'good agricultural practice' being produced. These are constantly under review. At the same time, various groundwater protection measures have been, or are being, introduced by MAFF and the NRA.

The restrictions on Autumn applications of organic manures in the proposed NVZs means that additional storage capacity may have to be installed by farmers or applications may have to go further afield. About 10% of Anglian Water's sewage sludge disposal sites could also be affected by NVZ designation, far fewer in the Severn Trent region (these are the two water undertakings with the largest area of designated NVZs). NVZ designation will have virtually no impact on sewage sludge disposal in Scotland.

All water undertakings have reviewed their existing and future sewage sludge disposal strategies in line with the tighter controls on sewage effluent required by the EC Urban Waste Water Directive (91/271/EEC). This is most significant for those currently using disposal to the sea - an option which will no longer apply after December 1998. The two major options are incineration (perhaps with heat recovery) and land application or disposal (landfill). Several of the Region Councils in Scotland have opted for increased applications to land. Application to the land is less attractive for large cities since transport of the sludge presents a serious problem.

WRc and the Forestry Commission have undertaken a long-term (10 yr) study of the use of sewage sludge as a forest fertilizer and WRc and some water utilities are currently evaluating the potential benefit of sludge applications for short rotation energy coppice.

The Royal Commission on Environmental Pollution is currently reviewing Soil Protection and is expected to report towards the end of 1995. This could influence future legislation on sludge disposal to land.

R & D

- determine dose-response-time curves and better models for determining the factors controlling the efficiency of nitrogen utilization from slurry, manure and sludge applications
- review evidence for the extent and possible impact of persistent, mobile trace organics from sewage sludge applications on groundwater.

REFERENCES

Department of the Environment (1989). *Code of Practice for Agricultural Use of Sewage Sludge*. London: Department of the Environment.

Foundation for Water Research (1993). Assessment of the environmental impact of recycling sewage Sludge to agricultural Land. *Research Report FR0350*. Marlow Foundation for Water Research.

Jones, K. C. and S. R. Wild (1991). Organic chemicals entering agricultural soils in sewage sludges: screening for their potential to transfer to crop plants and livestock. *Research Report FR0169*. Marlow: Foundation for Water Research.

Hall, J. E (1993). Sludge strategy. *Water & Water Treatment* (September, 1993): 110-111.

MAFF (1991). *Code of Good Agricultural Practice for the Protection of Water*. London: Ministry for Agriculture, Fisheries and Food.

MAFF (1993a). *Solving the Nitrate Problem*. London: Ministry for Agriculture, Fisheries and Food.

MAFF (1993b). *Review of the rules for sewage sludge application to agricultural land. Soil fertility aspects of potentially toxic elements*. London: MAFF.

Parkinson, R. J (1993). Changes in agricultural practice. In '*Nitrate: processes, patterns and management*', eds. T. L. Burt, A. L. Heathwaite and S. T. Trudgill, pp. 321-339. Chichester: Wiley.

Author: D G Kinniburgh, BGS

Reviewers: A R Agg, FWR
R Oake, Thames Water Utilities
K Pugh, North East RPB
P Smith, NFU

SUBSURFACE METHANE

PROBLEM STATUS

In the UK, a large proportion of the total methane emissions to the atmosphere is derived from subsurface sources, principally landfill and coal mining (Table 1). Agriculture also makes a significant contribution.

TABLE 1. CURRENT ESTIMATES OF THE UK EMISSIONS OF METHANE TO THE ATMOSPHERE (FROM BELLINGHAM *ET AL.*, 1994).

Source	Best estimate (Mt/a)	Range (Mt/a)
Landfill	1.93	0.63-4.16
Animal respiration	1.07	0.96-1.20
Animal waste	0.47	0.33-0.60
Coal industry	0.77	0.54-0.96
Gas leakage	0.45	0.34-0.56
Offshore oil & gas production	0.10	0.08-0.11
Stationary combustion	0.07	0.03-0.11
Other	0.07	0.01-?
TOTAL	5.0	3.6-7.2

Methane gas derived from subsurface sources is of immediate concern in the construction and mining industries because it forms potentially explosive mixtures with air, and because methane, and the gases normally associated with it (especially carbon dioxide), have a suffocating potential. Abandoned coal mines may pose methane emission risks post-closure on a local scale. Methane is also of longer-term concern because it is a potent greenhouse gas that is increasing in concentration in the atmosphere. Methane can be transported as a dissolved gas in groundwater or migrate laterally through the unsaturated zone and can therefore accumulate at some distance from its origin.

RELATED ISSUES

Landfill

TRENDS

As far as is known from the very limited amount of data available in the open literature, most shallow groundwaters in the UK either contain no detectable methane, or contain very low concentrations, usually much less than 1 ml STP per litre (Table 2). No studies have monitored changes with time but there is no reason to believe that these will change significantly in the near future.

TABLE 2. CONCENTRATIONS OF METHANE GAS FOUND IN SOME UK GROUNDWATERS (FROM HOOKER AND BANNON, 1993).

Location	Methane (ml STP/l)	Partial pressure (atms)	T (°C)
Chalk, London Basin, >70m depth[1]	$<1.7\times10^{-2}$	$<4.0\times10^{-4}$	10
Crystalline and metamorphic rocks, Scotland[2]	$<1.3\times10^{-5}$	$<3.1\times10^{-7}$	10
Permo-Trias brines, Wessex Basin, 1700 m depth[3]	1.8	0.096	70
Carboniferous strata, Abbeystead tunnel[4]	40	0.955	10

[1]Darling (1985), [2]Darling and Bath (1986), [3]Darling (1981), [4]Bath *et al* (1988)

The generation of methane from landfill sites will reflect the growth in the mass of material landfilled, its composition and the management of the sites. Official projections suggest that landfill emissions of methane could increase by a factor of three over the next 30 years. The composition of landfill gas changes with time, and after an initial phase of methane release lasting perhaps 5 years, methane emissions tend to decline as the organic-rich material is depleted and the landfill returns to aerobic conditions. Emissions from deep-mined coal are likely to decline as the UK mining industry further reduces in size but there could be continuing risks locally, possibly in new situations as the water flow paths change in response to changes in pumping.

Alterations to the groundwater flow pattern near landfills brought about by changes in groundwater pumping or recharge may alter the spatial distribution of methane in groundwater. Capping of landfill sites may encourage greater lateral transport of methane. Where the landfill gas is vented, flared off or used as an energy source, the methane load to groundwater will be reduced.

CONTEXT CHANGES

The greatest changes in UK methane emissions to the atmosphere are likely to be brought about by the increased use of landfill gas as an energy source, and the statutory need to reduce the emission of greenhouse gases. Emissions of methane from coal mining and agriculture are declining. The DoE has recently interpreted the Convention on Climate Change as requiring that anthropogenic emissions of each greenhouse gas, including methane, should be returned to 1990 levels by 2000, ie increased emissions of methane cannot be traded against reduced emissions of carbon dioxide.

LEARNING CURVE

Origin of subsurface methane and atmospheric emissions

Although the processes involved in methane production and oxidation are relatively well understood, the 3D distribution of methane-bearing strata in the UK and the concentrations of methane in UK groundwaters are less well understood, largely because of lack of data.

Methane, CH_4, is a gas that is mostly derived from the reduction of carbon, normally organic carbon. However, in formation waters, methane can also be derived from the decarboxylation of acetate ions. Methane can be produced by microorganisms (biogenic methane) or purely by chemical means following the burial, compression and heating of organic material (thermogenic methane). Methane can also be derived from the partial oxidation of organic-rich shales. Large quantities of methane are adsorbed by British coals and this is slowly released on exposure of coal to air (Creedy, 1991). Current estimates suggest that in the UK about 15 m^3 of methane is released per tonne of coal mined (Williams and Mitchell, 1994).

Methane currently occurs at a concentration of 1700 ppbv in the atmosphere and is increasing at the rate of about 10 ppbv per year. Globally, the largest sources of methane to the atmosphere are from paddy fields, swamps and marshes and from the exhalations of ruminants. The current best estimate of the total UK methane emissions to the atmosphere is 5.0 Mt/a with lower and upper bounds of 3.6 and 7.2 Mt/a (Table 1). The largest uncertainty in the present inventory concerns landfill.

Methane as a hazard

Several serious methane explosions have occurred in the UK in recent years, eg Abbeystead in 1984 (Orr *et al.*, 1991) and Loscoe in 1986 (Williams and Aikenhead, 1991). The source of methane at Abbeystead has not been unequivocally identified but is thought to have been a deep geological source while that at Loscoe was derived from a neighbouring landfill.

All those engaged in underground excavations should be aware of the potential dangers of methane gas. While these hazards have been appreciated for a long time by those working deep underground, the dangers were not fully appreciated until recently by those engaged in shallow excavations and tunnels. A recent publication from BGS and CIRIA (the Construction Industry Research and Information Association) provides a comprehensive background to the problem, particularly from the perspective of the construction industry (Hooker and Bannon, 1993). It highlights situations where problems are most likely to occur and how future potential problems can be minimized.

Migration in groundwater

Although methane is only a problem when it is present in the atmosphere, it is quite soluble in water (it has a similar solubility to that of oxygen) and is transported in the direction of the groundwater flow. It can therefore accumulate away from its immediate site of formation. There is very little information on the concentration of methane in most UK groundwaters although new methods of continuously monitoring methane in groundwater using diffusion cells have recently been tested and might be appropriate for monitoring methane migration near landfills (Lewin and Bradshaw, 1993). When subsurface methane comes into contact with air, it is gradually oxidized to carbon dioxide and water with the production of heat. This normally occurs in the unsaturated zone. The heat produced can sometimes be observed by thermal imaging or by its effect on local vegetation.

There are essentially four sources of methane likely to affect construction: deep-seated natural gas, coal mine gas, landfill gas and gas from shallow sources including gas main leaks. The source can often be identified from the known geology and hydrogeology of the area, from the other gases present and from the stable isotopic composition of the methane.

PERSPECTIVES

Research is currently being carried out on underground gas migration (mostly of hydrogen but some methane) from proposed deep underground radioactive waste repositories (AEA Technology). Models for gas migration are also available.

There is some concern that various groundwater problems, including enhanced concentrations of subsurface methane, may arise from recent colliery closures.

BENEFITS AND BENEFICIARIES

High concentrations of dissolved methane in groundwater are undesirable since they are likely to lead to the accumulation of hazardous concentrations of methane in the air of poorly ventilated places. The precise location of this accumulation is difficult to predict in advance. Methane is also a potent greenhouse gas and so emissions need to be minimized.

Beneficiaries include the Waste Regulation Authorities, National Rivers Authority, Departments of Environment and Energy, Health and Safety Executive, local authorities and all those in industry who work underground.

RESPONSE

As a result of the recent methane-induced explosions and concern about global warming, there has been increased interest in subsurface methane by both government and industry. This has resulted in a closer look at the issues involved. The Department of Environment has contracted BGS to review the relevance of methane in planning and development as part of its research into the distribution of natural contamination in Great Britain (Appleton *et al.*, 1994).

A number of public bodies including the former Warren Spring Laboratory, ETSU, the Watt Committee on Energy and the National Physical Laboratory have been actively engaged in refining the estimates of the UK methane inventory. Bellingham *et al.* (1994) give a critical appraisal of where new measurements need to be made. Such inventories will need to be published regularly as part of the UN Convention on Climate Change signed in Rio de Janeiro in 1992.

R & D

- develop better estimates of methane emissions, particularly from landfill sites, including the methane fluxes in groundwater
- carry out a national survey of methane in UK groundwaters and link to the local geology and hydrogeology
- identify new sources of high-methane groundwaters, eg near landfill sites, and improve guidelines for where methane accumulations might occur.

REFERENCES

Appleton, J. D., M. P. Bannon, F. Fordyce and P. J. Hooker (1994). Review of the relevance of carbon dioxide, methane and oil seeps to planning and development in Great Britain. *BGS Technical Report* **WP/95/1/R**. Keyworth: British Geological Survey.

Bellingham, J. R. *et al.* (1994). The UK methane emissions inventory: a scoping study on the use of ambient measurements to reduce uncertainties. *NPL Report DQM* **98**. Teddington: National Physical Laboratory.

Creedy, D. P. (1991). An introduction to geological aspects of methane occurrence and control in British deep coal mines. *Q. J. Eng. Geol.* **24**: 209-220.

Hooker, P. J. and M. P. Bannon (1993). *Methane: its occurrence and hazards in construction.* Report 130 Construction Industry Research and Information Association London: CIRIA.

Lewin, K. and K. Bradshaw (1993). *Continuous monitoring of methane in groundwater*. ed. W. Howe. London: HMSO.

Orr, W. E., A. Muir Wood, J. L. Beaver, R. J. Ireland and D. P. Beagley (1991). Abbeystead outfall works: background to repairs and modifications - and lessons learnt. *J. Inst. Water Envt Manag.* 5: 7-20.

Williams, A. and C. Mitchell (1994). Methane emissions from coal mining. In *'Mining and its Environmental Impact'*, ed. R. E. Hester and R. M. Harrison, pp. 97-109. Cambridge: Royal Society of Chemistry.

Williams, G. M. and N. Aikenhead (1991). Lessons from Loscoe: the uncontrolled migration of landfill gas. *Q. J. Eng. Geol.* **24**: 191-207.

Author: D G Kinniburgh, BGS

Reviewers: N S Robins, BGS
P J Hooker, BGS
A R Agg, FWR

UNREGULATED RURAL SUPPLIES

PROBLEM STATUS

Background

A significant number of private water supplies in the UK are groundwater sources located in rural areas where mains supplies are either not available or have not been connected for some reason.

Many are being taken from minor aquifers which are classified as moderately or highly vulnerable to pollution. These include both fractured, hard rocks (common in the west and north of the UK) and shallow aquifers.

The groundwater catchments of many such sources are localised, so the potential for local intensive land uses, discharges to soil or subsoil, pollution loads, or rock mineralisation to affect the wholesomeness of the supply is high. As most owners of such sources have little concept of their vulnerability, protection is reliant on whatever treatment is being provided by the owner,

The scale of exploitation (see below) suggests that there may be many sources which do not meet wholesomeness criteria and some of these may present a real health hazard. There are many cases of gastroenteritis affecting visitors who drink private water supplies, where the owners have built up an immunity.

Thee is a considerable amount of data, though that for nitrates and pesticides is more limited. Nevertheless no systematic overall study has yet been undertaken to provide a perspective on particular aspects of concern and relate them to causal factors.

Such a study, backed up by the development of appropriate techniques for groundwater investigations in such rocks, are a necessary step to increase our understanding of the situation so that authoritative and practical guidelines can be developed to help maintain the potability of such groundwaters and properly protect private supplies.

The scale of the problem

The DWI report 'Drinking Water 1993' states that there are about 50,000 private water supplies in England and Wales serving about 30,000 people. The equivalent figures for Scotland taken from 'Drinking Water in Scotland 1993' are about 27,000 private water supplies serving about 125,000 people. No figures are yet available for Northern Ireland.

UK as a whole (and taking account of the fact that some owners do not register sources because of local authorities' powers to condemn supplies) there may be nearer 100,000 such sources serving over 500,000 people. Most of these sources are groundwater sources - typically boreholes, wells or tapped springs.

These sources meet real needs - often including drinking water requirements in the absence of a mains supply. The most common uses are for domestic purposes and/or agricultural needs, but many hotels, golf clubs, retirement and nursing homes, hospitals, and camp sites are also reliant on such sources. The bottled water market makes use of hundreds of such sources.

Private water supplies predominate in the more rural and upland areas, particularly in areas dominated by hard, fissured or fractured rocks which contain minor resources of groundwater of little strategic significance.

Private water supplies in urban areas tend to have different pollution problems - contamination by chlorinated solvents from industrial practices being quite common in the West Midlands, and contamination from contact between rising groundwater and pilings occurring in parts of London.

Protection issues are complex - many source catchments extend under someone else's land and are subject to uses which the source owner cannot control. The reality is that many have limited or inadequate protection arrangements. "Water quality at the tap" surveys by environmental health officers indicate that in some areas over half the supplies would fail wholesomeness criteria if untreated (Craun, 1985).

Groundwater surveys carried out by the NRA and others confirm that inadequate groundwater quality is indeed often the cause, though inadequate protection of source works from surface pollution often complicates the picture. Reasons include pathogenic bacteria, nitrate/ammoniacal nitrogen, acidity and raised metal concentrations, and to a lesser extent atrazine/other biocides.

Apparent man-made causes include:

- poor borehole and well design
- proximity and density of septic tank effluent disposal systems
- inadequate storage/handling/disposal of chlorinated solvents and biocides
- farm and stockyard drainage systems
- sludge disposal and waste to land practices.

Elevated concentrations of naturally-occurring metals occur in some unbuffered groundwaters in non-carbonate terrains - possibly accentuated by effects of 'acid rain'. This can complicate the situation when pollution is also taking place.

RELATED ISSUES

Microbiological contamination
Sewers, soakaways and septic tanks

TRENDS

The use of small private sources is generally thought to be declining throughout the UK and Northern Ireland, though note should be taken of a recent rise in applications for private water supply licences in some NRA regions to replace public water supplies and save costs.

Though local authorities have requisitioning powers, small scale developments in the countryside often rely on private effluent disposal, increasing the scale of risk from septic tank effluents, for example in rural communities (Gerba and Bitton, 1984).

Elevated concentrations of naturally-occurring metals occur in some unbuffered groundwaters in non-carbonate terrains - possibly accentuated by the effects of 'acid rain'.

Monitoring has improved since the introduction of new regulations in 1991. The monitoring of private water supplies is now carried out by individual local authorities and improvement programmes are being prepared where necessary.

CONTEXT CHANGES

Farming practices are changing and this may accentuate particular risks. Such changes will vary locally. For example, the increased risk of pollution from atrazine and simazine as a result of increased maize production in the South West (particularly relevant to set-aside land). Other risks from farmland, for example from the "mismanagement" of general agricultural wastes, may fall as a result of MAFF and NRA waste management planning initiatives targeted at farmers.

The continued deposition of 'acid rain' could lead to a further increase in the concentrations of trace metals in poorly buffered groundwaters over time. Although the emission and deposition of sulphur-containing compounds (largely from the burning of coal) is likely to continue to decline, the deposition of nitrogen-containing compounds is likely to increase.

The Private Water Supplies Regulations 1991 for England and Wales and the corresponding Regulations for Scotland (1992) and Northern Ireland (1994) now regulate private water supplies to ensure a measure of protection to consumers. Any future changes to wholesomeness criteria from EC or UK legislation are likely to arise through better understanding of specific health risks. This may focus attention on particular aspects of the problem.

LEARNING CURVE

Knowledge of the hydrogeological characteristics of shallow, hard rock aquifers is variable. It is unusual for there to be sufficient information from which the catchment of a source can be determined precisely. Background transmissivities and storativities are generally low to very low. Unless significant overburden exists, groundwater subcatchments tend to be localised with good hydraulic connections to nearby springs or streams. The dominant bedrock flow mechanism is commonly fissure flow with short flow paths resulting in groundwaters with shorter residence times. This tends to accentuate the concern about pollution risks.

NRA sampling at a limited number of sites has tended to endorse the concerns of environmental health officers as a result of their "water quality at the tap" surveys. Man-derived contaminants commonly include pathogenic bacteria, and nitrate. Others found include ammoniacal-N, biocides, and chlorinated solvents.

PERSPECTIVES

Many small domestic and agricultural abstractions are common law rights which are exempt from abstraction licensing controls. Their existence is often unknown to the authorities, except where surveys for other purposes have identified them. In England and Wales, the Environmental Health Offices are obliged to protect unregulated sources. Mapping the position of all such sources would help the local authorities to do this effectively.

Pollutants often include local septic tank effluent (often unsuspected recycling!) agricultural point sources (farm yards, stores or their drainage systems) as well as particular land uses in the catchment (eg where atrazine is used on maize crops). In most cases the catchment serving the source is not known with any degree of certainty or may only become known as a result of pollution from an obvious point source.

Recent publications include a DoE Departmental Review of Rural Water Supplies and Sewerage (August 1994) which contains a number of recommendations for improved controls/guidance on sewage disposal and treatment arrangements and a Manual of Treatment of Private Water Supplies, issued by the Drinking Water Inspectorate, giving advice on different treatment methods.

DoE circular 24/91 asks local authorities to begin to prepare and maintain a public register of private water supplies containing certain specified details in preparation for the implementation of an EC Directive on the Freedom of Access to information on the Environment.

BENEFITS AND BENEFICIARIES

A better understanding of the scale of the problem, improved methods of investigation and guidelines for small source and groundwater resource protection would benefit:

- source owners and those using such supplies (these include private individuals and consumers of bottled or piped water derived from such sources) to achieve effective source protection and appropriate treatment

- contractors and consultants involved in source investigations or in source construction, maintenance or protection works

- MAFF and the farming community to revise relevant land use guidelines

- DoE to develop or revise relevant legislation to enhance protection and control of particular types of land use or development, and to consider the benefits of requiring more thorough data as part of source location registration.

RESPONSE

The NRA and others have become more conscious of the need to monitor and protect groundwaters effectively, and local authority planning and development control departments are more willing to restrict unsuitable developments.

The NRA have a duty to protect private sources. The NRA and other authorities have the power to classify Source Protection Zones, and to seek controls on developments in source catchments. This work is currently targeted at developing zones for public water supply and other major sources in major aquifers, which serve large numbers of people. It will be many years before zones are drafted for most smaller sources. There is real concern because resulting restrictions might apply to a third party who owns the land which forms the catchment area, who may not be the owner or user of the source concerned.

Local authority environmental health departments to better understand likely hydrogeological and geochemical (rather than man-made) influences and seek appropriate derogations in particular aquifers.

Discharge consenting powers also help limit pollution risk. However single septic tank discharges are generally approved by a default tick-list system; if the applicant confirms that particular situations apply, the consent is automatic.

R & D

- review effectiveness of contaminant attenuation and degradation processes

- evaluate the scale and type of groundwater quality sampling that is appropriate to properly monitor the extent of such pollution

- review how monitoring should focus to reflect areas for concern

- review whether it is possible to separately identify baseline (ie natural) groundwater quality and thus enable the scale of groundwater contamination resulting from different sources of pollution or land uses (ie man-influenced groundwater quality data) to be evaluated

- identify what pilot studies are needed to help the impact of particular types of land use which appear to be generating health hazards for groundwater sources, and what best practice guidelines are appropriate for such uses to minimise risks

- determine what practical guidance should be given to owners on best practices for constructing, maintaining and protecting sources in particularly susceptible areas

- determine what derogations are appropriate under Regulation 4 of the Private Water Supplies Regulations on the basis of natural water chemistry

- review the detailed hydrogeological processes that affect aquifer susceptibility to pollution, eg the variation of pollution risk with distance

- determine the most appropriate methods of quantitative and qualitative hydrogeological investigation/risk assessment, taking account of the likelihood that detailed site data may be limited

- review the protection policies, if any, that are most appropriate to protect unregulated groundwater sources from different potential threats

- evaluate the threat from septic tank tile drainage (Canter and Knox, 1985) and the extent of natural degradation of domestic waste in septic systems and the impact on the groundwater protection (Wilhelm and Cherry, 1994).

- develop a 'sourcebook' of natural baseline groundwater quality data for hard rock provinces in the UK, identifying locations where particular natural factors are likely to exist which can detrimentally affect potability and wholesomeness

- develop best practice guidelines for (i) baseline surveys of groundwater quality with particular regard to health hazard issues, and for (ii) source investigation, construction/maintenance and protection works

- review appropriate land use controls for typical hard rock hydrogeological situations and source arrangements, possibly augmented by a trial to assess the value of creating a technical register of such sources to help ensure their effective protection from particular land uses or development proposals.

REFERENCES

Canter, L. W. and R. C. Knox. 1985. *Septic Tank Systems: Effect on Groundwater Quality*. Chelsea, MI: Lewis Publishers. 336 pp.

Craun, G. F. 1985. A summary of waterborne illnesses transmitted through contaminated groundwater.

J Environ. Health 48: 122-127.

Gerba, C. P. and G. Bitton. 1984. Microbial pollutants: their survival and transport pattern to groundwater. In: *Groundwater Pollution Microbiology*, ed. G. Bitton and C.P. Gerba. pp. 65-88. New York: John Wiley and Sons.

Wilhelm, S. and J. A. Cherry. 1994. Biogeochemical Evolution of Domestic Waste Water in Septic Systems. *Ground Water* 32: 905-916.

Author: C Tubb, NRA

Reviewers: N S Robins, BGS
W M Edmunds, BGS
M Eggboro, NRA
I H MacDonald, DoE

WASTEWATER REUSE

PROBLEM STATUS

On a global scale, the very rapid urban growth of the last few decades has produced increasing demands for potable water. As a consequence of growth and industrialisation, surface water resources are either fully utilised or now of poor quality, and groundwater resources are becoming increasingly important. The improved coverage in large cities of water-borne sewerage systems produces enormous volumes of wastewater for disposal. By reusing this wastewater in a carefully managed way, water is conserved, groundwater quality is maintained and the overall situation improved, especially in arid areas. Increasing recognition is being given to the value of wastewater as an important resource, and strategies for reuse are likely to become more widely adopted. Wastewater is commonly reused in the surface water context in the UK - sewage effluent is discharged into rivers and subsequently abstracted downstream.

While the principal focus is on more arid environments, resource constraints in humid temperate zones may also lead to increased interest in the scope for resource augmentation by wastewater reuse. In the UK context, this is likely to imply the enhanced use of aquifer storage by the artificial recharge of partially-treated wastewater. To design and manage such schemes, adequate knowledge of the hydrogeology, infiltration processes and the movement and attenuation of pollutants is required. In this respect, the behaviour of viruses, and persistent organic compounds remains the most problematic.

Discounting the spreading of animal slurries on farmland, which is referred to in the *Sludge Utilization* paper, the use of wastewater for groundwater recharge is not yet greatly developed in the UK. The most comprehensive experience of recharge with partially-treated wastewater comes from the Chalk in southern England.

RELATED ISSUES

Microbiological contamination
Resource protection and vulnerability
Rising water levels
Source protection
Sustainable yield

TRENDS

It is likely that the growth in average public water supply demand in the future will be quite modest. For example, the NRA anticipate a 2%, 10% or 25% increase in demand by 2021 (from a 1991 base) depending on a Low, Medium or High demand scenario, respectively (NRA, 1994). A key feature in the demand forecasting is the extent to which demand management, particularly the introduction of domestic metering and leakage control, will curtail the underlying growth in demand.

It is likely that the use of partially-treated wastewater to augment groundwater resources will increase in the future. The increasing demand is likely to come especially in the south-east of England, where groundwater resources are most heavily exploited and most susceptible to the impacts of drought. If climatic change produces rises in sea level, increasing the risk of saline intrusion, and declining recharge, then increasing importance will be attached to the reuse of wastewater.

CONTEXT CHANGES

Interest in wastewater reuse has been stimulated by rising water demand and the pressures this places on conventional water resources. This interest has been further stimulated by the drought conditions experienced in the UK in recent years, and perhaps by longer-term concerns about the impact of possible global climatic change on water resources. The increased generation of wastewater that follows from increased water usage provides a large potential resource that could be utilised to improve the overall management of water resources. Wastewater reuse is one of the options available - the key issue is the yield and cost of recharge.

LEARNING CURVE

Considerable experience has built up in recent years of the operation of wastewater reuse schemes. The most comprehensive data come from schemes in which partially-treated wastewater is infiltrated into unconsolidated sediments in the more arid parts of the United States (Bouwer, 1991) and in Israel (Idelovitch & Michail, 1984). By monitoring their performance over long periods, infiltration has been demonstrated to be an effective method of treatment for wastewater. The slower and less continuous the infiltration, the better the quality of the recharge is likely to be. The soil and unsaturated zone are capable of removing some but not all contaminants. For pathogens, the lower the hydraulic loading and the smaller the infiltration rate, the more effective is the biopurification. Protozoa and bacteria are normally eliminated completely, but viruses may be more persistent and mobile. The risk of deterioration of microbiological quality is unlikely to be the main constraint on wastewater recharge.

The total nitrogen content of wastewater is high, and large-scale wastewater recharge can produce unacceptable concentrations of nitrate or ammonium in groundwater. Continuous discharge of untreated wastewater produces anaerobic conditions, permitting ammonium to reach the water table. If more oxidised secondary effluent is applied at low rates, nitrification occurs and nitrate is transported downwards with the recharge. Cyclic applications which allow alternate wetting and drying can be used to control and reduce nitrogen concentrations in recharge.

Heavy metals originating in the wastewater are likely to be adsorbed within the system itself or at shallow depths in the soil. The mobility of metals depends on the pH-Eh conditions imposed by the wastewater irrigation. Only in markedly acidic conditions is transport of heavy metals likely. Wastewater infiltration usually causes some increase in groundwater salinity, and chloride may provide an early indication of the impact of wastewater reuse.

Infiltration through the soil is also very effective in removing biodegradable organic carbon. Nevertheless, a plume of elevated organic carbon concentrations in groundwater is often observed in groundwater below and down gradient of wastewater recharge areas. This suggests a persistent fraction remains, which might contain trace organic compounds some of which may be potentially toxic. These could produce problems for subsequent water treatment.

For the United Kingdom, recent operating experience was summarised by Beard and Giles (1990) and Foster *et al.* (1994). Infiltration of wastewater with primary or secondary treatment into the Chalk aquifer produced, in most cases, total removal of bacteria and viruses, reduction in high initial concentrations of ammonia and phosphorus, attenuation of metals, and reduction in BOD and dissolved organic carbon. Beard and Giles (1990) also reviewed the various engineering methods of infiltration which had been employed in schemes on the Chalk. Of land spreading, deep lagoons, excavated ditches and french drains, they suggested that ditches were the most effective way of combining efficient infiltration and effective pollutant removal.

PERSPECTIVES

The maintenance of supply of potable water is the fundamental priority for water utilities. The security of raw water quality, consistent with treatment requirements on a site-by-site basis, is also important. Thus the reuse of wastewater must provide additional resources of good quality without jeopardising the quality of existing groundwater resources. Planning wastewater reuse schemes will therefore require careful selection of a combination of appropriate hydrogeological conditions, recharge methodology and wastewater quality to allow adequate time for pollutant attenuation. The operation and impact of schemes will need to be carefully monitored.

If wastewater is reused for irrigation, care will have to be taken to ensure that public confidence in food and other agricultural products is maintained, and that all possible health and safety risks are taken into account.

BENEFITS AND BENEFICIARIES

Research into the topic of wastewater reuse has been primarily directed at understanding the behaviour of the various types of pollutants in the wastewater and the effectiveness of their removal for a range of soil and aquifer materials. In addition, research has addressed the issue of operation and management of wastewater reuse and artificial recharge schemes, to determine which methods of introducing the water into the aquifer are most effective at balancing efficient infiltration and effective pollutant removal. Different methods of infiltration have very different land requirements, and this aspect is of considerable importance to operators.

Understanding the controls on pollutant removal and knowledge of the effectiveness of removal allows the level of treatment required before infiltration to be determined in each case. This has a major bearing on the cost of wastewater reuse. This knowledge also allows the recovery of the recharged water to be designed, in terms of positioning and distance of recovery wells.

If wastewater reuse is demonstrated by research to be effective without causing significant deterioration to the underlying groundwater, and if it allows water to be recovered which meets the appropriate quality criteria without major investment in additional treatment, then it could become more widely used. This would be of benefit to the water industry, especially in areas where groundwater resources are most heavily utilised. The efficient recycling of nutrients not only saves money but it also minimises deleterious effects such as eutrophication.

RESPONSE

At present, wastewater reuse is a much more active issue in semi-arid environments than in temperate European countries. The best established schemes using partially or fully treated wastewater to recharge aquifers are operated in Israel and in the drier states of the southern US. Agricultural irrigation with untreated wastewater, with subsequent infiltration to underlying aquifers, is widely practised in Mexico.

Interest in wastewater reuse could be stimulated elsewhere in the world, including the UK, if the possible effects of climatic change on water resources become clearer. One potential beneficial use of wastewater in the UK could be to meet some of the increasing requirement for irrigation water in the drier parts of eastern and southern England.

There can be problems with the clogging of recharge boreholes with fine particles if the recharge water is only partially treated.

R & D

- review and evaluate current use, and scope for use, of wastewater in the UK
- evaluate design of irrigation and/or infiltration systems
- study persistence and transport of viruses
- determine persistence and transport of trace organic compounds originating in the industrial component of wastewater.

REFERENCES

Beard, M. J. and D. M. Giles (1990). Effects of discharging sewage effluents to the Chalk aquifer in Hampshire. In '*Chalk: Proceedings of the International Chalk Symposium*', Brighton, 1989, Thomas Telford, 597-604.

Bouwer, H. (1991). Groundwater recharge with sewage effluent. *Wat. Sci. Tech.*, 23: 2099-2109.

Crook, J., D. K. Ammerman, D. A., Okun and P. E. Matthews (1992). *Guidelines for Water Reuse*. pp 254. Camp, Dresser and McKee.

Foster, S. S. D., I. N. Gale and I. Hespanhol (1994). Impacts of Wastewater Use and Disposal on Groundwater. *BGS Technical Report* **WD/94/55**. Keyworth: British Geological Survey.

Idelovitch, E. and M. Michail (1984). Soil-aquifer treatment: a new approach to an old method of wastewater reuse. *J. Wat. Poll. Control Fed.* **56**: 936-943.

NRA (1994). *Water: Nature's Precious Resource*. HMSO:London.

Authors: M E Stuart, BGS
P J Chilton, BGS

Reviewers: P J Shaw, NRA
S L Longstaff, Thames Water Utilities Ltd
I H MacDonald, DoE