BRITISH GEOLOGICAL SURVEY

Technical Report WD/98/19
Environment Agency R&D Technical Report W160

Groundwater Tracer Tests: a review and guidelines for their use in British aquifers

R S Ward, A T Williams, J A Barker*, L J Brewerton and I N Gale

* Professor of Hydrogeology, University College, London
BGS, Honorary Research Associate

This report is the result of a study jointly funded by the British Geological Survey's National Groundwater Survey and the Environment Agency's National R&D programme.

Environment Agency Dissemination status
Internal: Release to Regions
External: Public Domain
Ref No. SO-06/98-B-BBAV

Statement of use
This report summarises available information and data on tracers and tracer tests applicable to their use in resolving groundwater issues in British aquifers. A protocol for borehole tracer tests is given as well as summaries of tests undertaken. The report is intended to provide practical guidance to both practitioners and regulators to promote greater use of groundwater tracer tests.

Cover illustration
Sequential conductivity profiles in a single borehole dilution test in the Chalk aquifer in East Yorkshire. Further details are given in Box 4.3.

Bibliographic Reference
Ward, R S, Williams, A T, Barker, J A, Brewerton, L J, and Gale, I N. *1998*. Groundwater Tracer Tests: a review and guidelines for their use in British Aquifers. *British Geological Survey Report WD/98/19*

British Geological Survey, Keyworth, Nottingham 1998

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Keyworth, Nottingham NG12 5GG
☎ 0115 936 3100 Telex 378173 BGSKEY G
Fax 0115 936 3200
e-mail: sales@bgs.ac.uk www.bgs.ac.uk

Murchison House, West Mains Road, Edinburgh, EH9 3LA
☎ 0131 667 1000 Telex 727343 SEISED G
Fax 0131 668 2683

London Information Office at the Natural History Museum, Earth Galleries, Exhibition Road, South Kensington, London, SW7 2DE
☎ 0171 589 4090 Fax 0171 584 8270
☎ 0171 938 9056/57

St Just, 30 Pennsylvania Road, Exeter EX4 6BX
☎ 01392 278312 Fax 01392 437505

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 01232 666595 Fax 01232 662835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491 838800 Fax 01491 692345
e-mail: hydro@bgs.ac.uk

Parent Body
Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire
SN2 1EU
☎ 01793 411500 Telex 444293 ENVRE G
Fax 01793 411501

ENVIRONMENT AGENCY
Rivers House, Waterside Drive
Aztec West, Almondsbury, Bristol, BS12 4UD
☎ 01454 624400 Fax 01454 624409
e-mail: enquiries@environmentagency.gov.uk

Printed in England for the British Geological Survey by
Alphagraphics Ltd, Nottingham

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FOREWORD

The use of tracer tests to resolve a range of groundwater related issues was identified as a generic research need in the strategic study of groundwater in the UK (Grey et al, 1995). That study was sponsored by The UK Groundwater Forum and, as members, both the British Geological Survey and the Environment Agency (then the National Rivers Authority) had an interest in promoting knowledge about, and the use of, tracer tests in relation to groundwater movement and contaminant transport. A three-year project entitled 'Groundwater Tracer Studies' was developed and co-funded by these two organisations and was initiated in October 1995.

The main objectives of the project were to gather information on groundwater tracer tests, to provide guidance to those wanting to undertake tests and to promote their use through dissemination of this information to potential practitioners. This was achieved through literature and data searches to provide an assessment of current best practise, both in the UK and internationally, and wide involvement of the user community through a questionnaire and consultation and dissemination meetings. The impact of the study and the guidance provided in the report needs to be reviewed and updated after one to two years.

ACKNOWLEDGMENTS

This report has been compiled by the authors with a great deal assistance from a large number of people from a variety of organisations. The project was monitored and directed by the Steering Committee whose members are listed below. Dr Darminder Chadha, Environment Agency, N E Region was particularly supportive during initiation of the project and through provision of additional funding to carry out tracer tests in the Yorkshire Chalk and the Corallian Limestone aquifers. In connection with this field work, invaluable input was also provided by John Watkins of Yorkshire Water Services through provision and analysis of bacteriophage.

Useful input and feedback was received from those who responded to the questionnaire distributed at the beginning of the project in March 1996, participants in the Seminar on Groundwater Tracer Tests held at the Geological Society on 8 October 1996 and participants in the dissemination meeting held at BGS Wallingford on 10 February 1998. Where possible, knowledge and experience aired at these meetings by tracer test practitioners has been incorporated in the report. Lists of those involved in the meetings are given in the Project Record which was supplied to the Environment Agency on completion of the project.

Valuable input was received from several Environment Agency staff , particularly those involved in facilitating field work, and BGS staff involved in the field and laboratory work, particularly John Davis and Rachel Leader. The authors also wish to acknowledge the contribution made by Dr George Darling on environmental tracers and Laura Coleby for compiling the database of tracers.

The final draft of the report was given a detailed and constructive peer review by Dr Tim Atkinson of the University of East Anglia, as well as staff of the Environment Agency's National Centre for Groundwater and Contaminated Land, Solihull. Three students carried out tracer tests as projects for their MSc studies that were related to the project and were supported by BGS University Collaboration funding. Anita Furey (UCL), Edel O'Hannelly (UEA) and Jonathan Parry (UEA) undertook these studies, the products of which are listed in Table 1.2 of this report.

STEERING COMMITTEE

Mr Ian Gale	*BGS Project Manager, Hydrogeology Group, Wallingford*
Mrs Ann Williams	*BGS , Hydrogeology Group, Wallingford*
Dr Rob Ward	*BGS, Fluid Processes and Waste Management Group, Keyworth*
Mr Paul Shaw	*Environment Agency Project Manager, Southern Region, Worthing*
Dr Darminder Chadha	*Environment Agency, North East Region, York*
Mr John Ellis	*Environment Agency, Southern Region, Worthing*

EXECUTIVE SUMMARY

Tracer tests have been used in hydrogeological studies to improve understanding of groundwater flow paths and measure travel times as well as in contaminant transport studies. However, experience is predominantly in karst or karst type aquifers to demonstrate connectivity and measure travel times. In intergranular aquifers, tracer tests are used much less frequently because of the slower movement of groundwater and the greater potential for dilution. Tracer tests have the potential for wider use, not only to help resolve issues they have been traditionally used for, but also to estimate dilutions, establish flow mechanisms and measure groundwater seepage rates. Tracer tests can also provide estimates of porosity of aquifers and other parameters needed in transport modelling. The widespread use of small scale tracer tests could lead to a database of parameters analogous to those obtained from pumping tests.

Uncertainties about how much of which tracer to use, as well as how best to perform a tracer test, can restrict their use, as can the potential risks of contaminating water supplies. This report attempts to reduce these risks by providing a collation of experience, discussion and guidance on tracers and tracer tests as well as a protocol for undertaking tests, including regulatory aspects.

There is not a single 'ideal' tracer that can be recommended for all groundwater studies. An 'ideal' tracer follows the same pathway as the substance being investigated. Movement of particulates, e.g. oocysts, will be very different from the movement of water soluble material which will be very different from the movement of non-aqueous phase liquids (NAPLs). Guidance on selection of the most appropriate tracer to meet the objectives of a tracer test is given.

Hydrodynamic dispersion (the spreading of the tracer due to spatial variations in the flow velocity), diffusion (the transport of molecules or ions as a result of gradients in concentration) and sorption onto the surfaces of particles and minerals can have significant impacts on the movement, timing of arrival and concentration of tracers at the sampling points. These, and other factors need to be accounted for in planning a tracer test.

There is a wide range of substances that can be used as tracers in the resolution of groundwater issues, including suspended particles (e.g. spores, fluorescent microspheres), solutes (e.g. sodium chloride, halogen anions), dyes (e.g. fluorescent, optical brighteners), gases (e.g. sulphur hexafluoride, CFCs), isotopes (e.g. stable, radioactive nuclides, tritium), temperature, microbiological (e.g. bacteriophage) and environmental tracers. The latter group have been introduced into the environment by natural or anthropogenic processes. Their presence and concentration can be used to determine the likely origin and movement of groundwater over longer time periods - years, decades or even millennia. Tracers in this group include tritium, stable isotopes of hydrogen, oxygen, nitrogen, sulphur and carbon as well as radiocarbon and chlorofluorocarbons (CFCs).

A database of tracers has been compiled including their chemical and physical parameters, potential use and suppliers and, where applicable and available, toxicological data. The gaps in this database demonstrate the lack of knowledge about some of these potential tracers. These gaps will need to be filled before effective use can be made of these tracers.

The most commonly used tracers in groundwater studies are the fluorescent dyes Fluorescein (Uranine) and Rhodamine WT, the optical brightener Photine CU, and bacteriophage; the latter being the only tracer that the Environment Agency is currently confident in using towards Public Water Supply wells. Only this limited number are commonly used because of their effectiveness and acceptability through previous use. This should not restrict use of alternative tracers, such as new fluorescent dyes or radioactive tracers, if they are more suitable.

Tracer tests can be as varied as the issues they are designed to resolve. They can range in scale from laboratory experiments to field site scale (tens or hundreds of metres) to regional scale (kilometres). At field and regional scales, tests can be carried out with or without boreholes and the scope for tests of increasing complexity increases with the number of boreholes available. Tests can be carried out under natural groundwater gradient conditions or under forced gradient (pumping) conditions. The advantages and limitations of this range of tests are described and a detailed protocol is given for the two of the most useful tests: Single Borehole Dilution Test and Radially Converging Tracer Test.

Detailed planning of tracer tests is imperative if they are to succeed. A clear conceptual model of the hydrogeological environment is needed in order to facilitate the choice of tracer(s) and the quantity of tracer(s) required. Protocols for injection and sampling, or tracer detection, need to be well planned and monitored in order to maximise the chances of positive results and avoid spurious readings. A positive result proves connectivity but a null result proves little. Health and Safety issues need to be fully considered and the involvement of local Environment Agency staff at an early stage is key to the test being sanctioned and supported.

Analytical methodologies should be included in the planning process to ensure that all the necessary data are collected, either manually or automatically. Tracer test analysis can range from a positive measurement/sighting of the injected tracer to complex modelling that reveals aquifer transport parameters. The latter should be carried out by a groundwater modeller, who should be involved in the planning of the test. Models should also be used in the planning process to optimise the quantity of tracer used and in selecting monitoring times and frequency. When analysing tracer test results, the factors of scale dependency and uniqueness of interpretation need to be evaluated and special consideration needs to be given to tests in fractured, porous aquifers such as the Chalk. Non-unique solutions can be constrained by use of several tracers and by other sources of data such as pumping test results.

The report has brought together current experience and knowledge of tracer tests and provided detailed guidance to facilitate and stimulate future tests. Issues that need to be addressed have been identified, including the fate of bacteriophage in pumping wells, the lack of data on the toxicology of some potentially useful tracers and the extent to which tracer tests can provide aquifer transport parameters useful for the delineation of borehole catchment zones. A review of the impact of the project and the report, as well as an update of the tracer and tracer test databases, needs to be undertaken in a couple of years in order to maintain the momentum of interest generated.

1 INTRODUCTION

1.1 Background to the project

Effective management of groundwater - its abstraction, protection and remediation - relies on an ability to understand and predict the impact of human activities and natural stresses on groundwater quantity and quality. Where uncertainty restricts our ability to predict precisely and accurately groundwater behaviour, potentially excessive caution must be exercised which may have significant economic implications. All aquifers are heterogeneous to some extent and this is a significant source of uncertainty in groundwater development and management.

The major UK aquifers (Chalk, Sherwood Sandstone, Jurassic Limestone) are all to some extent fractured and fracturing is itself an important form of heterogeneity. Variable fracturing density, extent and connectivity combined with differing matrix porosities further increase aquifer heterogeneity and our ability to predict pollutant migration.

This uncertainty is far greater for water quality, especially pollutant migration, than for water quantity. The effects of variability in aquifer properties on flow tend to average and, therefore, average properties, such as transmissivity, suffice. In contrast, the effect of heterogeneities on pollutant transport tend to be additive, causing growing uncertainty in prediction as distance of travel increases. This contrast is reflected in the relative confidence that can be placed in flow models while scepticism is almost invariably necessary in accepting the results of solute transport models. Delineation of source protection zones, as recommended in the Environment Agency's Policy and Practise for the Protection of Groundwater, 1998 is carried out using flow models only. This can be understood given the need for wide application of the policy and a reasonable level of defensibility.

Over time our knowledge of the structure and intrinsic properties of our aquifers may improve to a point where it will become possible to model transport with acceptable confidence. However, this will take considerable time and in the meantime we need to build an approximate picture of pollutant transport in our aquifers. A medium-term approach, advocated by this project, is to use tracers to determine transport behaviour in aquifers directly, cutting across the complexities of the processes, aquifer parameters and heterogeneity. The assumption that underlies this project is that if tracer test application can become widespread and more frequent, a body of information on the transport properties of our aquifers can be built up. These data can then be fed into ever improving predictive models.

1.2 The need for tracer tests and tracer test data.

The strategic study of groundwater research needs in the UK (Grey et al 1995) identifies tracer testing as a generic research activity which can be useful for solving many problems. However that study does not give any indication of how tracer tests should be used or how they should be carried out. The scope of this report is to make tracer testing a more widely available tool and to direct hydrogeologists and researchers towards the problems which tracer testing can help solve.

Tracer test results not only provide site specific data, they also provide insights that help in the conceptualisation that is necessary for model development and the data that will be needed for model calibration and validation. The examination of chemical signatures in waters in both the saturated and unsaturated zones has shown clearly that the approximations which are made when water resources issues are discussed are not suitable when water quality is the issue. The research initiated by the discovery of the increasing concentrations of nitrate in groundwater in the 1970's, highlighted the lack of understanding at that time of the processes involved in water flow in fractured, dual-porosity media. Since that time, the complexities of flow in other, apparently more simple aquifer systems has also been questioned. For instance, the extent and degree of fracturing in the Sherwood Sandstone aquifer means that it should probably be considered as a dual-permeability formation.

That these conclusions can be drawn about aquifer behaviour by consideration of environmental tracer chemistry implies that a great deal can be learned from well designed and controlled artificial tracer tests. The difficulty with using environmental tracers, or pollution incidences is that not enough is known about the input to the aquifer. In a designed tracer test the input of the tracer is controlled and other influences on the test, such as rainfall events, can be monitored during the period of the test. The disadvantage of artificial tracer tests are i) that chemicals have to be introduced into otherwise clean waters, thus leading to possible aquifer contamination and ii) the timescale over which is feasible to carry out a controlled test may be too short for some important mechanisms, e.g. chemical diffusion, to have a significant effect. Despite these problems a lot can be learnt from tracer tests if they are properly designed and analysed.

For groundwater models to be useful as tools for predicting transport behaviour there is a requirement for a background understanding of the relative importance of the various processes which are relevant. One of the ways in which models can be made more representative and reliable is having a good database of relevant transport parameters. In much the same way as an understanding of the range of possible variations in hydraulic conductivity makes flow modelling accepted even when the parameters used are sometimes different to site specific values, it is important that the range of possible transport properties is understood. One way of developing such an understanding is for tracer testing to be carried out in a wide range of different aquifers, and the results collated and compared. In this context, a comparable test design should be used.

In order to encourage the wider use of tracer tests a protocol has been developed that can be used with reasonable success with few, if any, specialized staff at a relatively small cost widely across the UK aquifers. It is hoped that, given the protocol, tracer testing could be added to other investigation activities, such as pumping tests, by investigators who appreciate the need for building a strategic body of information on the transport properties of UK aquifers.

To summarise:
1) the desire to improve our knowledge of water quality and contaminant transport will be best satisfied if a large body of test data on contaminant transport values can be built up. This is what drives the hope that tracer tests will become routine
2) in order for tracer testing to become routine, a wider cross-section of practising hydrogeologists must become aware of its potential and how to apply it. Thus one aim is to educate
3) Practical guidance is needed. The second aim of the report is to provide this through the protocol presented in Appendix A

1.3 Typical problems where tracer tests can be applied

Tracer tests are often considered at the early stages of an investigative programme of work. In most cases the idea is then quickly forgotten because of the perceived complexities and the lack of positive experience. In many cases tracer tests are not appropriate, and it is because of this that many groundwater researchers have had negative results which has coloured their perception of the value of the tracer test as a useful investigative tool.

In many cases the distances and the timescales required to trace natural groundwater flow mean that tracer tests are not suitable tools. Also the dilution of the tracer in the aquifer is a significant consideration, which can result in a lack of tracer detection. However, under the right conditions a tracer test can provide information about the aquifer that it would be almost impossible to obtain by any other methods.

Tracer testing has been used predominantly in karst or karst type aquifers. In these aquifers recharge areas and discharge points can usually be readily identified. The problem is one of connection and travel times. Occasionally tracers are not recovered because of a misunderstanding of the hydrological regime resulting in the tracer travelling to a different point or at an unexpected speed. There is a large body of literature relating to karst tracer tests which has not been reviewed in detail for this project. The karst literature has been searched to find details of types of tracers, detection methods and limits and injection techniques. This information is of direct relevance to tests performed in the major UK aquifers.

Tracer testing at a much smaller scale is also performed in intergranular media. The best reported tracer test is that performed at the Borden airforce base in Canada (e.g. Cherry et al 1986). Over a period of several years numerous tracer tests have been performed using a purpose built piezometer array consisting of 47 piezometers implaced at different depths in an area of only 0.5 ha. These tracer tests were performed under controlled conditions and the results have been subjected to intense scrutiny. However it is doubtful whether the results of this work are of anything other than academic interest as it is not possible to transfer them to other areas.

Typical applications of tracer tests include the following:

- Proving connections between recharge and discharge points e.g. sinkholes and springs

- Estimating travel times e.g. between natural recharge and discharge points or between boreholes

- Estimating dilutions

- Establishing groundwater flow mechanisms e.g. fracture v. intergranular flow

- Measuring groundwater seepage rates (Darcy velocity)

- Measuring porosity

However it must be stressed that tracer tests are not applicable to ALL investigations of this type. For instance, whilst it is true that positive detection of a tracer will prove a connection, non-detection proves nothing. Thus, at the planning stage the implications to the investigation of non-detection must be considered. These considerations, and others are discussed in greater detail in Chapter 5.

1.4 Scope of the Project

This three year project has focused on the needs of the user community, with the overall target of making tracer testing more accessible. To do this a number of tracer tests have been performed and a further number supported. A tracer test protocol has been developed which should enable inexperienced hydrogeologists to perform a radial flow tracer test with a good chance of success.

A review of the types of chemicals etc. which can be used to carry out a tracer test has been completed. This work has included a consideration of the aspects of toxicological terminology required to understand the data that are available in the wider literature. The more important properties of the tracers have been discussed in detail in Chapter 3 and Appendix E contains the listing of a database of these properties which has been compiled for the project. The project has not included any new investigation into the toxicological aspects of tracer use and thus, can only report knowledge which presently exists.

A digest of the types of tracer test which might be considered has been enhanced by including brief descriptions of instances where the different test types have been successfully applied. This should give guidance as to the possible uses of the different sorts of tests. The experience gained through performing tracer tests, discussions with practitioners both in the UK and elsewhere and an extensive review of the literature has reinforced the view that planning is a very important part of a successful tracer test. The procedure to be followed, which is recommended in Chapter 5, follows on from this understanding.

1.5 Environment Agency responsibility and legislative framework

The Environment Agency, established under the 1995 Environment Act, has the role to maintain and protect the quality and yield of groundwater resources. The Agency has statutory duties under the Water Resources Act 1991 (as amended by the 1995 Act) to control discharges into groundwater and has adopted the former National Rivers Authority policy document Policy and Practice for the Protection of Groundwater. Whilst this document is non-statutory it provides a framework for decision making and allows the Agency to respond to consultations in a consistent manner according to duties set out in the 1995 Act.

Groundwater tracer tests normally involve the introduction of a substance into the ground or directly into the saturated zone and, as such, could theoretically be controlled under the consenting provisions of the Water Resources Act 1991. However, as they usually involve only a discrete short term low volume release, legal control by consent or conditional prohibition notice is not normally exercised.

The Groundwater Directive (EC Directive on the Protection of Groundwater Against Pollution by Certain Dangerous Substances - 80/68/EEC) refers to two lists of substances of particular concern in regard to risks of pollution to groundwater. Substances of greatest concern, which are included in List I, must be prevented from entering groundwater. This effectively precludes the injection of tracers which comprise or include such substances. Entry into groundwater of substances included on List II, which are of lesser concern, must be restricted in order to prevent pollution. Advice on the acceptability of tracers including List II substances should be sought from the Environment Agency. Table 1.1 shows the families and groups of substances controlled under the Directive.

Notwithstanding this, it is essential that all proposed tracer tests are referred to a groundwater protection officer at one of the Agency's Area offices so that any potential impact on local abstraction can be assessed on an individual basis. If any well, borehole or spring used for drinking water supply could potentially be impacted it will be normal practise for the Agency to consult with the Water Company (if a public water supply source is involved) or the Local Authority Environmental Health Officer (if the source is a private supply). Water Companies have responsibility under the Water Supply (Water Quality) Regulations 1989 to ensure that the water supplied remains wholesome. If there was any possibility that a tracer test could cause the abstracted groundwater to pose any risk to public health the Water Company (and/or the Agency) would refer the matter to the Drinking Water Inspectorate.

Table 1.1 List I and List II substances as defined by EC Groundwater Directive (80/68/EEC) (taken from Appendix 1 of EA Groundwater Protection Policy)

LIST I OF FAMILIES AND GROUPS OF SUBSTANCES	**LIST II OF FAMILIES AND GROUPS OF SUBSTANCES**
These substances should be prevented from being discharged into groundwater	Discharges of these substances into groundwater should be minimised.
List I contains the individual substances which belong to the families and groups of substances specified below, with the exception of those which are considered inappropriate to List I on the basis of a low risk toxicity, persistence and bio-accumulation Such substances which with regard to toxicity, persistence and bio-accumulation are appropriate to List II are to be classed in List II	List II contains the individual substances and the categories of substances belonging to the families and groups of substances listed below which could have a harmful effect on groundwater.
1. Organohalogen compounds and substances which may form such compounds in the aquatic environment. 2. Organophosphorus compounds 3. Organotin compounds. 4. Substances which possess carcinogenic, mutagenic or teratogenic properties in or via the aquatic environment(1). 5. Mercury and its compounds. 6. Cadmium and its compounds. 7. Mineral oils and hydrocarbons. 8. Cyanides.	1. The following metalloids and metals and their compounds: 1. Zinc 2. Copper 3. Nickel 4. Chrome 5. Lead 6. Selenium 7. Arsenic 8. Antimony 9. Molybdenum 10. Titanium 11. Tin 12. Barium 13. Beryllium 14. Boron 15. Uranium 16. Vanadium 17. Cobalt 18. Thallium 19. Tellurium 20. Silver 2. Biocides and their derivatives not appearing in List I 3. Substances which have a deleterious effect on the taste and/or odour of groundwater and compounds liable to cause the formation of such substances in such water and to render it unfit for human consumption 4. Toxic or persistent organic compounds of silicon and substances which may cause the formation of such compounds in water, excluding those which are biologically harmless or are rapidly converted in water into harmless substances. 5. Inorganic compounds of phosphorus and elemental phosphorus 6. Fluorides 7. Ammonia and nitrites
(1) Where certain substances in List II are carcinogenic, mutagenic teratogenic they are included in category 4 of List I	

As all tracer tests are, by definition, site specific it is essential that this process of site by site assessment and consultation always occurs and it is the Environment Agency who will facilitate the process. A proforma letter for notifying the Environment Agency of intent to undertake a tracer test is provided in Appendix A (Page A-15). This letter gives recommendations for information that should be provided to the Agency. No ground water tracer test should be undertaken without approval of the Agency.

1.6 Scope of this report

This report has been organised in such a way as to make it accessible at a number of levels. It is hoped that reading the entire report will not prove too onerous a task, but it is recognised that not all who are interested in tracer testing will have an equal interest in every aspect. Thus there is some repetition of information, in an attempt to make most of the main chapters (Chapters 3-7) self - sufficient. More specialised and detailed information has been put in appendices as has the proposed 'Tracer Test Protocol'. Numerous reports and technical notes have been produced during the project. The content of these has been synthesised in various parts of this report and a comprehensive list is given in Table 1.2.

Table 1.2 Reports produced during the project period

Groundwater Tracer Studies: Environment Agency Interim Report R&D 587/2/S
The use of environmental tracers in Chalk hydrogeology. BGS Technical Report WD/96/26
Heath House Tracer Test: Data Report. BGS Technical Report WD/96/74
Banterwick Barn tracer test: Data report. BGS Technical Report WE/96/XC
The use of tracer tests in UK aquifers. In: Kranjc (ed) 1997 *Tracer Hydrology 97* pp 299-301
The use of groundwater tracers for assessment of protection zones around water supply boreholes - A case study. In: Kranjc (ed) 1997 *Tracer Hydrology 97* pp 369-376
Dilution tests at Banterwick Barn. MSc thesis University College London A Furey
An investigation of groundwater flow in the Chalk aquifers of Berkshire and Cambridgeshire, using analysis of single borehole dilution tests. MSc thesis University of East Anglia J Parry
Groundwater tracing dye retardation in Chalk and the implication for forced-gradient convergent radial-flow tracer test analysis. MSc thesis University of East Anglia E O'Hannelly
Tracer tests at Kilham, N Yorkshire. BGS Technical Report WE/96/45

2 PRINCIPLES

2.1 `Ideal' tracer

For hydrogeological investigations an `ideal' tracer is one which accurately follows the same pathways through an aquifer as the substance being investigated. This is necessarily a vague statement. An ideal tracer for imitating the transport of pesticides will not be the same as that chosen to imitate the transport of a dense non-aqueous phase liquid.

2.2 Groundwater flow

Groundwater flow in saturated porous media is almost invariably described by Darcy's law which states that the volumetric flux, q, in a saturated porous medium is proportional to the gradient of the head, h, and the hydraulic conductivity, K:

$$q = - K \nabla h \qquad (2.1)$$

Darcy's law is known to fail for high velocity flows such as are often encountered close to wells and in fissures. It is also questionable whether it holds for very small pore sizes, especially for viscous fluids.

When only gross volumetric flow through an aquifer is of interest then it is adequate, at least on a scale of many times the aquifer thickness, to consider the flow to be essentially horizontal. However, it must be recognized that flow rates vary considerably at different depths, and travel times along flowpaths descending to different depths can vary considerably. This is particularly important when protection zones around wells are being delineated.

Advection (or convection) is the term used to describe movement with the bulk flow of water within an aquifer. The speed of this movement, v, is given by the volumetric flux (q) divided by the kinematic porosity (n_e)[1].

$$v = q / n_e \qquad (2.2)$$

Kinematic porosity may be significantly different to total porosity, especially in fractured media. This has important implications for travel times and, hence, source protection.

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[1] The porosity that is of importance when groundwater flow velocities are being considered represents the saturated pore space which contributes to the flow. De Marsily (1986) defines the ratio of the volume of water able to circulate to the total volume of rock as the 'kinematic porosity'. However, the term 'effective porosity' is more commonly used for the same quantity, even though it is also used for specific yield. 'Kinematic porosity' is preferred and is used in this report to encourage its wider adoption.

2.3 Dispersion and diffusion

2.3.1 *Dispersion*

The term *dispersion* refers to the process of spreading during transportation: solutes, particles and heat are all dispersed in groundwater. The processes of matrix diffusion and adsorption both have dispersive effects, however the term *hydrodynamic dispersion* refers more specifically to spreading due to spatial variations in the flow velocity, mainly caused by branching of the flow paths. (Unfortunately, some writers use the term hydrodynamic dispersion to represent both advective and diffusive mechanisms of spreading.) The process takes effect at many scales, from the pore-scale upwards.

Dispersion arises because of the detailed variations in flow velocity in pores and fractures mainly due to the complex splitting and joining of paths but also due to flow velocity variations in single paths. If we had complete knowledge of the flow distribution and could model that distribution we would not have to introduce the concept of dispersion. Thus, dispersion is a process which is inseparable from flow itself, and depends on the properties of the medium.

When flow is intergranualar, Darcy's law is only valid at scales which are large (~10 to 100 ×) compared to the pore-spacing scale, because it is only at these scales that the ensemble of velocities can be averaged to give a reliable mean. The same scale relation applies to dispersion even though dispersion effects depend on variability in velocity. Thus the minimum scale at which dispersion can be treated as a Fickian process is the one at which the ensemble of velocities is just large enough for its variance to be reliably sampled. This will be much the same as the minimum Darcian scale.

Variance in groundwater velocities may increase at larger scales for two reasons - either new, infrequently spaced, pore elements with higher-than-average velocities may be encountered as scale is increased, as in fractured media, or there may be continuous variation in ensemble means from place to place, as in cases where Darcian permeability is inhomogeneous. The critical factor is the ratio of the region-of-interest's scale to the pore spacing scale, for the largest fastest flow paths. If this is greater than about 100, only Darcian inhomogeneity need be considered as a source of dispersion (though dual-porosity diffusion may also contribute). If less than about 10, specific flow paths will appear as lines of preferred transport and Fickian dispersion models will not be appropriate.

Because Fickian dispersion results when velocity variations are equally distributed about the mean, any skewing of that distribution gives non-Fickian dispersion. In double porosity media, where a significant amount of the velocity distribution is close to or at zero, non-Fickian behaviour is very significant.

Hydrodynamic dispersion presents two major problems: (a) there is no generally accepted physical and mathematical description for heterogeneous media, and (b) it is difficult to perform experiments (e.g. tracer tests) to accurately quantify the dispersive characteristics of rocks.

If advective transport could be fully characterized throughout the system, there would be no additional dispersion phenomenon to consider. So, strictly speaking, dispersion is not a process in its own right, it is rather an expression of the fine (often random) detail of the advection process. Dispersion must therefore be related to the advective model (conceptual or mathematical) in use, particularly to its scale of averaging.

In pollution studies this spreading phenomenon is normally beneficial as it tends to reduce concentrations, and the view is sometimes taken that it should be ignored in modelling studies and regarded as providing a ‘safety margin'. It has certainly proved difficult to make a rational choice of parameter values to put into dispersion models (particularly because of scale-dependent behaviour), which also tends to negate the value of including dispersion. Perhaps a middle path is to include dispersion in some relatively simple manner (to avoid computational problems associated with accurate modelling of the convection-dispersion equation - see below) and then to present results for a range of characteristic dispersion parameters.

The flux, J_{Disp}, due to hydrodynamic dispersion is normally represented by an equation analogous to Fick's law for diffusion:

$$J_{Disp} = -D\nabla c \qquad (2.3)$$

where D is the dispersion tensor and c is the concentration.

The term longitudinal dispersion is applied to dispersion in the direction of flow while transverse (or lateral) dispersion applies to dispersion perpendicular to that direction. Vertical transverse dispersion is usually smaller than horizontal transverse dispersion.

The normal approach to modelling transport in a dispersive medium is via the so-called convection-dispersion equation, which contains longitudinal and transverse dispersion coefficients, D_L and D_T. These coefficients are normally considered to increase in proportion to the absolute value of the velocity, v, so, for example, $D_L = \alpha_L \left| v \right|$, where α_L is known as the dispersivity, and has units of length.

Dispersion coefficients for single fractures are more likely to show proportionality to the square of velocity rather than to the velocity. More work is required on the process of flow in natural fractures if it is to be better described and modelled.

Experimental determinations of longitudinal dispersivity in the Chalk aquifer were reviewed by Black and Kipp (1983) who also carried out experiments of their own. Values vary from a few centimetres (for laboratory-scale measurements) to a little over 100 m, at the field-scale. However, since matrix diffusion has such a major effect in the Chalk, during any attempt to determine dispersivity from a field experiment care must be taken to account for diffusion.

2.3.2 *Diffusion*

Molecular and ion diffusion involves the net transport of a molecule or ion as the result of gradients in concentration (strictly activity), pressure (strictly fugacity) and temperature. It occurs as the result of random collisions of the molecules or ions due to their thermal motion (Brownian motion). Diffusion obeys Fick's first and second laws and is described by a diffusion coefficient. The diffusion of molecules and ions is analogous to that of heat.

Diffusion can also occur as a result of gradients of electrical potential (electro-osmotic diffusion); this process is normally negligible in aquifers.

In laboratory and field investigations (especially tracer tests) it is often observed that when a pulse of solute passes through a subsurface system to a detector, the observed concentration/time *breakthrough curve* is asymmetrical, with a long ‘tail' indicating significant delay of part of the solute (although some tailing is expected even for Fickian dispersion). In very general terms, such behaviour can be interpreted as being due to some local non-equilibrium effect. A physical mechanism that can give such effects is that where water is mobile in part of the system and (effectively) immobile in the rest of the medium. An exchange of solute between these parts of the system must be taking place due to molecular diffusion (Brownian motion).

A term often used to describe such systems is *double porosity* media. Much work in recent years has been directed towards understanding the behaviour of such media, which include a wide range of rock types from aggregated soils to fractured hard rocks. Amongst UK hydrogeologists, the main interest in such systems has focused on the problems of transport in the Chalk aquifer, although the same mechanism must be of importance in other aquifers. Recently, the double porosity concept has been extended and generalized to what are referred to as *hierarchical porous media* (Cushman 1990). Although such considerations are mostly theoretical, they do appear to have important potential for application to UK aquifers, particularly the Chalk.

The effects of matrix diffusion on contaminant transport in fractured rock was noted by Foster (1975) in relation to the observed migration of tritium in the Chalk aquifer. Adopting the same mechanistic view, Young et al (1976) provided an interpretation of the distribution of nitrate in the Chalk. More recently, Lawrence et al (1992) showed that slow diffusion of solvent from the matrix water in the zone of fluctuation of the water table gave rise to intermittent long-term pollution with the matrix acting as a secondary source of pollution.

The importance of diffusive processes in tracer tests depends to a large extent on the 'speed' of the test. The length of time for which the tracer is in contact with aquifer will have a significant effect on the importance of the different processes. This in turn affects the aquifer characteristics which can be measured during the test. As an example, Table 2.1 gives an estimate of how deep into the matrix a tracer will penetrate in a typical Chalk. It can easily be seen that most tracer tests will not reveal much about the matrix of a Chalk aquifer.

Table 2.1 Effect of diffusion times

Time	Distance
2 days	1 cm
200 days	10 cm
200 years	2 m

2.4 Scale effects

Dagan (1982) and Gelhar and Axness (1983) provided the foundations for determining field-scale flow and dispersion parameters in heterogeneous formations in terms of the geostatistical properties of the permeability. However, this leaves the problem of estimating the statistical parameters for real systems. Another problem is that some later theoretical work (e.g. Neuman et al 1987) is not consistent with these earlier findings and the discrepancies have yet to be resolved.

Non-Fickian behaviour has been seen in many tracer tests, in particular it has been noted that longitudinal dispersivity increases with the scale of the study (e.g. Lallemand-Barres and Peaudecerf 1978 and Anderson 1979). Neuman et al (1990) plotted a large number of dispersivities against length scale (on a log-log plot) and fitted straight lines:

$$\alpha_L = \begin{cases} 0.017\, L^{1.5} & L \le 100\, m \\ 0.32\, L^{1.5} & L \ge 100\, m \end{cases} \tag{2.4}$$

(units of metres). They interpreted the results on the basis of a quasilinear dispersion theory (Neuman and Zang, 1989; Zang and Neuman, 1989) and concluded that the media must have a self-similar log hydraulic conductivity structure with a mean fractal dimension of 1.75.

Although these results are of potential value, it cannot be recommended that they should be applied other than with great caution. In particular, it remains for a significant body of measurements of dispersion coefficients to be made for British aquifers. Also, the effects of matrix diffusion, especially in the Chalk, will make the application of any simple dispersion theory questionable.

Molz et al (1983) suggest that the scale required for Fickian dispersion conditions to apply will seldom be reached in practice, and that more effort should be directed towards the accurate determination of hydraulic conductivity.

Only a small fraction of the literature on this topic has been mentioned. Apart from mathematical, laboratory and field work, much effort has been put into numerical simulations. So much effort has been invested in the scale problem that Lehr (1988) was prompted to write: "... solute transport in aquifer formations is advective dominated and thus the dispersion term can be omitted, for all practical purposes ..." and, further, that: " ... it is time for all but a few elite groundwater scientists to be realistic and get on with more pressing problems." This view has much merit provided dispersion in the form of preferential flow, especially in fractured rocks, is dealt with as a special case.

2.5 Travel times

Travel times through an aquifer are of great importance when planning tracer tests. As explained above, the effect of hydrodynamic dispersion is to spread out the plume of tracer within the aquifer. However, consideration of Darcy's Law and the conservation of mass can give an indication of the expected travel time of an undispersed tracer.

Combining equations 2.1 and 2.2 and replacing the velocity, v, with $\Delta L/\Delta t$ and ∇h with $\Delta h/\Delta L$ the following equation for Δt is obtained:

$$\Delta t = n_e\,(\Delta L)^2 / K\,\Delta h \qquad (2.5)$$

This equation can be used to estimate the time it will take for water to travel from one point to another. The significant feature of this equation is that for a given head drop, the travel time is proportional to the square of the distance travelled, and so travel times increase rapidly with increasing distance (all other things being equal, a test over 100 m with a head drop of Δh takes 100 times longer than a test over 10 m with the same head drop).

2.6 Sorption of tracers and related phenomena

Many solutes are sorbed on the surface of other minerals and particles. Sorption reactions are particularly important for trace constituents. Very few solutes are not adsorbed at all which is one reason why it is so difficult to find good water tracers. Sorption reactions are important in retarding movement of contaminants through aquifers; equally sorption is also important in retarding the clean-up of polluted aquifers. Sometimes when a charged solute, normally a cation, is sorbed onto an oppositely charged surface it displaces another cation of equivalent charge from the surface. This is called *ion exchange*. Additionally a specific surface complex can be formed between solute and surface without an equivalent exchange. Sorption can also occur because of the non-specific forces that tend to attract all solutes to surfaces.

Various chemical and physical forces are involved in sorption processes, which are normally distinguished into a**d**sorption, which takes place at the surface of minerals, and a**b**sorption, which involves the movement of materials from solution to sites within the structure of the solid phase. Both these processes have the effect of retarding the tracer front as it moves through the aquifer. Thus the sorptive characteristics of tracers must be known in order that the results of tracer tests can be correctly interpreted. An equation for the relative average velocities of the water, v_w, and the solute, v_s, is:

$$\frac{v_s}{v_w} = \frac{1}{1 + K_d \frac{\rho_b}{n}} \tag{2.6}$$

where K_d is a distribution coefficient, ρ_b is the dry bulk density and n is the porosity of the aquifer material. The value of K_d depends on both the tracer and the aquifer material and can be greatly affected by the presence or absence of clays. The choice of the value to be used for porosity (n) in this equation is not always straightforward, particularly in the case of dual-porosity media in which part of the pore space may not be reached by the tracer

Certain combinations of tracer and aquifer material have a distribution coefficient which is effectively zero. These tracers are thus not affected by the aquifer and respond in the same way as the water. These tracers are known as `conservative tracers' and those which are retarded, or permanently held up in an aquifer are called `non-conservative'.

2.7 Survival of bacteria and viruses

The use of living organisms as tracers introduces a new parameter which must be considered when designing and interpreting tracer tests. The method of detection for most viruses (e.g. bacteriophage) and bacteria is by `culturing' the sample and counting the number of viable organisms within the sample. Thus the tracers are not detectable unless they survive. The `die-off' rate of most organisms is usually defined by means of a half-life (similar to that used for radioactive particles). This is because the organisms appear not to have a definite `life-span' but viable numbers reduce in an approximately exponential manner.

2.8 Other transport processes

The processes outlined above are not comprehensive. Other processes that will often effect the movement of tracers include: filtering, radioactive decay, and gravity movement (floating and sinking).

3. TYPES OF TRACER

3.1 Introduction

There are many different types of tracer available for use in tracing groundwater and pollutant movement. These may be artificial, anthropogenic or natural. Artificial tracers are those deliberately introduced to the aquifer for the purpose of the test e.g. fluorescent dyes. Anthropogenic tracers are those introduced to groundwater by mans activities e.g. Chlorofluorocarbons and tritium. Natural tracers are those normally present in the aquifer for example through water-rock interactions. Anthropogenic and natural tracers are sometimes grouped as environmental tracers.

There is a large body of information available about the substances which could be used as groundwater tracers. This chapter describes the types of tracers available and the choice of tracer for a study. Practical advice on the use of different tracers is given. The final section describes a database of information about tracers which has been obtained from the literature.

3.1.1 *Choice of tracer*

The choice of tracer depends on a number of factors, the most important of which is the reason for the test. Tracer testing may be used for several reasons or combinations of reasons, for example:

1. Establishing hydraulic connections
2. Determination of groundwater flow directions
3. Calculation of groundwater velocities
4. Determination of groundwater age
5. Establishing of groundwater provenance
6. Tracing the movement of pollutants

The behaviour of the tracer must be similar to that of the substance which is to be traced. If the test is to study groundwater movement, flowpaths and travel times then a substance which approaches an “ideal tracer” is essential. Many tests are designed to look at travel of substances other than the water itself, such as pollutants, in which case a tracer which mimics the properties of this substance will be of more use.

The ideal groundwater tracer moves with the groundwater without altering the flow. It must be inexpensive, easily detected in trace concentrations and stable for the length of the experiment. Background levels of the tracer in the aquifer must be low. The ideal tracer is easy and safe to handle and non-toxic to humans and environment (Davis et al, 1980).

Many chemicals are easily sorbed onto aquifer materials or affected by ion exchange or chemical reactions, some are unstable or affected by photochemical or radioactive decay, others cannot be detected at low concentrations or have high background levels. High concentrations of some chemicals can alter the density of the water thus altering flow patterns. Particulate tracers may be filtered by aquifer materials. Many chemicals are toxic to humans and/or the environment. Unfortunately the ideal water tracer does not exist, but the properties of some tracers make them more suitable to trace groundwater movement than others.

Some tracers which are limited in their ability to trace water movement, for example because they are strongly adsorbed, may be of use in determining the movement of pollutants with these properties through aquifer materials.

The suitability of any tracer will also depend on the background levels of the substance in the groundwater, the degree of dilution expected during the test, the detection limit of the tracer and the possible interference effects if using more than one tracer in a test. Finally the toxicity of the tracer must be taken into account.

It is also important to consider the environmental conditions in the aquifer when choosing a tracer. In particular the pH conditions and the mineralogy may make some tracers less suitable than others. Interactions between tracers and aquifer materials are often determined in laboratory batch or column tests prior to a field test.

Other important factors which have to be taken into account are:

1. equipment required for the test
2. number, type and quantity of sample needed
3. time required for tracer injection and sample point monitoring
4. type and availability of analysis required
5. overall costs of the test.

Some of these factors may result in a less than ideal tracer being chosen for the test. The limits of the tracer in the test environment must be then be taken into account.

3.1.2 *Toxicity*

Toxicology is the study of the adverse effects of chemicals on living organisms. The toxicity of substances used for tracer testing has been the subject of several reviews in the literature (e.g. Smart, 1984). However for many tracers there is little or no information in the hydrogeological literature. However studies may be found in microbiological journals, suppliers chemical data sheets and specialist literature. Often the data available for different tracers cannot be directly compared because of the different experimental conditions or techniques. General information about the toxicology of individual tracers is given, where available, in section 3.2.

The major factors influencing the toxicity of a substance are the routes of administration and the duration and frequency of exposure. A toxicology study may consist of comparisons of the substance structure with those of known carcinogens or mutagens followed by in-vivo and in-vitro tests to determine whether a substance is carcinogenic or mutagenic. Further tests may be carried out to determine whether it has the ability to irritate the skin or eyes or to determine the effects of the substance on reproduction and development. Additionally, chemicals may exhibit selective toxicity i.e. they can damage one kind of living matter without harming another. This makes it hard to predict the toxic effects in humans from experiments performed in another species.

Some tracers are more toxic than others. Some which were used in the past are no longer recommended. Tracers and their degradation products must not exceed the permissible toxicity thresholds set for man and the environment. Generally tracers are diluted to low concentrations and are used only episodically thus reducing their impact as potential toxicants.

Table 3.1 A glossary of common terms found in the toxicological literature (based on Furey, 1996).

Ames Test	popular in-vitro test using *Salmonella* to test for reverse or back mutations
Bioassay	measurement of the concentration or potency of a substance by its effects on living tissue
Delisted	no longer listed (or recommended) e.g. as a food colour
Epidemiology	study of epidemic disease including all forms of disease that relate to the environment and ways of life
Genotoxic	chemical that reacts with deoxyribonucleic acid (DNA)
In-vitro	describing biological phenomena that are made to occur outside the living body (traditionally in a test tube
In-vivo	describing biological phenomena that occur or are observed within the bodies of living organisms
Lethal Concentration (LC)	see lethal dose.
Lethal Dose (LD)	LD_{50} is the median lethal dose i.e. the single dose required to cause death in 50% of animals tested. Sometime other figures are quoted e.g. LD_{95}. This is sometimes also quoted as the lethal concentration.
Mutagenicity	the ability of a chemical to cause changes in the genetic material of the cell nucleus; it allows changes to be transmitted during cell division
Subcutaneous	situated, used or introduced beneath the skin
Toxin	toxic substances which are produced naturally
Toxicant	toxic substances which are produced by or are a by-product of anthropogenic activities

3.2 Types of tracer

This section reviews the different types of tracers available, their applicability to different tests conditions, examples of their use and details of their toxicology where known. Many types of substances have been used as tracers in hydrogeology. There have been a number of reviews on types and suitability of tracers (for example Davis et al (1980), Keswick et al (1982), Davis et al (1985), Smart & Laidlaw (1977)).

3.2.1 *Suspended particles*

Solid particles in suspension can be successfully used as tracers where groundwater flows in large conduits, but are generally not suitable in aquifers where the flow is intergranular as the particles will be filtered out. In conduits particles usually float on the water surface and are of a size and density so they do not settle out. Thus they travel faster than the mean velocity of the water (Davis et al, 1985). Particulate tracers are most useful for approximating the flow velocity and determining the flowpath.

Early particulate tracers used in karstic terrain to trace from sinkholes to springs were small pieces of paper with numbers printed on them as punched for example from computer cards (Davis et al, 1985).

The spores of the club moss *Lycopodium clavatum* have been used for tracing in karstic limestones (Gardner & Grey, 1976). The spores are cellulose bodies about 30 μm in diameter which are slightly denser than water. Some turbulence is therefore required to keep them in suspension. The spores can survive in polluted water, but do not perform well in slow moving water or in water with a high sediment concentration (Davis et al, 1985). The spores are resistant to environmental effects and are non pathogenic. The spores can be used in their natural state or stained before injection with fluorescent or non-fluorescent dyes so that multiple injections can be undertaken. Malachite Green, Bismark Brown, Magenta, Saffranine Alpha and Methyl Alpha have all been successfully used as dyes for spores (Smart and Smith, 1976). However, some of these dyes have been shown to be toxic (e.g. malachite green) and care should be taken with their use (Quinlan, 1986). Alternatively spores can be dyed with fluorescent dyes.

Sampling is done using plankton nets at springs and the spores examined under a microscope. Lycopodium spores only stay in suspension in fast, turbulent flow, so they probably travel faster than the average water velocity. Experiments comparing *Lycopodium* with fluorescent dyes have shown that *Lycopodium* travelled faster than fluorescein dyes (Atkinson et al, 1973) but slower than Rhodamine B dye (Buchtela et al, 1968). Recent work has used *Lycopodium* spores for tracing in a flooded mine to determine the degree of interconnection of shafts and galleries and velocity of the mine water (Wolksdorfer et al, 1997).

Yeast is a single celled fungus which is ovoid in shape. The cells (about 2 to 3 μm) are much larger than bacteria and viruses but smaller than *Lycopodium* spores. Bakers yeast (*Saccharomyces cerevisiae*) was successfully used for tracing downward movement through a sand and gravel aquifer over short distances by Wood & Ehrlich (1978). The survival of the yeast cells depends on the availability of nutrients in the environment.

Fluorescent microspheres made from plastic have recently been used as particulate tracers. They have been detected by epifluorescence microscopy and more recently by dissolving the beads in acetone followed by analysis with a fluorescence spectrophotometer (Ward et al, 1997). Epifluorescence microscopy is time consuming and impractical for large numbers or volume of samples. The second method can be applied to water or rock samples, other particulate material which may fluoresce is filtered out and large volumes of water can be analysed. It is important that the plastics used for the microspheres are neutrally or slightly negatively buoyant. Atkinson et al (1973) used plastic spheres but they floated and were unsuccessful. Harvey et al (1989) utilised microspheres with different surface characteristics and compared their movement with bacteria. Neutrally charged microspheres were less sorbed than microspheres with charged surfaces. The transport behaviour of these microspheres was substantially different from that of the bacteria. Ward et al (1997) reported the use of microspheres in field and laboratory experiments.

Micro-organisms are also particulate tracers and are discussed in detail in section 3.2.7.

3.2.2 *Solutes*

Many inorganic substances have been used as water tracers. Suitable substances must have a sufficiently high solubility in water at temperatures of about 10°C and the chemical state needs to be stable under the test conditions. During tests of long duration diffusion may become an important process. Self diffusion coefficients of frequently used ions are given in the tracer database (section 3.4).

Ions are prone to sorption and ion exchange. Adsorption is the physical attraction of the tracer to the surfaces of the aquifer material. The degree of adsorption is affected by the surface area and composition of the aquifer material and is therefore dependant on grain size, grain shape and packing, and the mineral composition. Ion exchange occurs when the ions in the tracer exchange with ions in the aquifer minerals. In most soils and rocks the cation exchange capacity is much greater than the anion exchange capacity thus cations are more prone to exchange than anions. The exchange capacity of rocks increases with decreasing grain size and increasing content of clay minerals and organic matter (Knutsson, 1968).

The most suitable solutes are the halogen anions: Cl^-, Br^- and I^-. Of these bromide is more suitable than chloride because background levels tend to be more stable and lower. The iodide ion is frequently unstable (Behrens, 1986), tends to be sorbed to a greater extent than bromide or chloride and is affected by microbiological activity (Davis et al, 1985). The presence of ionic tracers can be determined by chemical analysis of samples or by using an ion specific electrode.

Some organic anions such as benzoate and m-TFMBA are also suitable (Davis et al, 1985). These have very low background concentrations, are not adsorbed and are moderately stable. However they are expensive. Samples can be analysed using high pressure liquid chromatography (HPLC) to a high precision. This is a specialised technique which requires particular equipment.

Cations such as lithium (Li^+), potassium (K^+) and magnesium (Mg^{2+}) have been used but these are prone to ion exchange and adsorption and are generally less suitable than anionic tracers.

Sodium Chloride (NaCl) was among the earliest inorganic substances used as a tracer. It is simple to use, easy to detect, readily available and acceptable to the general public. It can be detected using a conductivity meter but this method may require a high injection concentration to obtain detectable levels above the background at the sampling point. However, high concentrations of NaCl (above 3000mg/l) increase the density of the solution sufficiently to alter flowpaths. High background levels, especially of chloride, may be present in some groundwater environments making this an unsuitable tracer.

The drinking water quality standard for chloride is 400 mg/l although chloride is not harmful to health. These standards should not be exceeded in water used for human consumption.

Chelating agents such as EDTA (ethylen-diamine-tetra-acetic-acid) have been used with In, Cr and Dy to form stable complexes. Complexes with La and Mn were unsuccessful because the central cation was sorbed resulting in loss of the tracer (Behrens, 1986).

3.2.3 *Dyes*

A number of dyes and related compounds have been utilised as tracers including non-fluorescent dyes, fluorescent dyes, dye-intermediates and optical brighteners. There are usually obtained in powder form or as a concentrated solution.

Non-fluorescent dyes absorb light in the visible spectrum and are detected by human eye or by absorption spectroscopy. The discoloration of ground or surface water is usually unacceptable to the general public and for the environment and prevents their use as groundwater tracers. However they have been used for example in soil studies and sewers. Some dyes used in the past have been found to be toxic and should not be used for groundwater tracing e.g. Malachite Green and Congo Red.

Fluorescent dyes are organic compounds. The molecules are composed of C, H and O in some cases with N, S and/or halogens. Most fluorescent dyes used for tracing are anionic, but rhodamine B is cationic. The fluorescent characteristic results from the configuration of the double bonds in the structure of the molecule (Behrens, 1986). Fluorescent dyes can be grouped as blue, green or orange based on the wavelengths at which they fluoresce. Examples of each dye type are given in Table 3.2. Dye intermediates such as Amino G Acid are compounds used in the manufacture of dyes but which do not form a dye in their own right. This distinction is rather meaningless as far as tracing is concerned as it is the ability to fluoresce that is of importance, not the ability to adhere to cloth which is the quality necessary for a substance to be categorised as a dye.

Fluorescent dyes absorb light at one wavelength (excitation wavelength) and emit it at another (emission wavelength) and can be detected at much lower concentrations than ordinary dyes. A filter fluorometer can be used for quantitative analysis of samples. Alternatively passive detectors composed of cotton wool (photine) or activated charcoal (fluorescein) can be employed for qualitative (positive or negative) results. Semi-quantitative results can be obtained from passive samplers by using a known mass of charcoal and volume of elutriant for desorption. By careful selection of filters for the fluorometer to minimize interference between dyes, three dyes (one blue, one green and one orange) may be distinguished in one sample.

Table 3.2 Classification of dyes into orange, green and blue based on their excitation and emission peaks.

Colour Group	Dye
Orange	Rhodamine dyes
	Eosine
Green	Uranine (sodium fluorescein)
	Lissamine FF
	Pyranine
Blue	Photine
	Naphthionate
	Amino G Acid (dye intermediate)

Fluorescent dyes exhibit different degrees of sorption and some are strongly adsorbed. These are more suitable for solute transport studies, where they are used to mimic adsorbing organic chemicals such as pesticides (Sabatini & Austin, 1991). Dyes which are less adsorbed are more applicable to studies of groundwater flow. Trudgill (1987) compared the adsorption of two fluorescent dyes and a dye-intermediate. Rhodamine B was found to be the most highly adsorbed with Lissamine FF and Amino G Acid less so. Experiments by Di Fazio and Vurro (1994) show that Rhodamine WT is retarded with respect to NaCl in column experiments. Smart and Laidlaw (1977) compared the adsorption of 8 fluorescent dyes onto kaolinite and humus sediment. Amino G Acid, Photein CU and Pyranine showed the most resistance to sorption to kaolinite, while Amino G Acid, Pyranine, Lissamine FF and Sulphorhodamine B were the most resistant to adsorption onto the humus. Tests reported by Reichert and Hotzl (1992) showed no retardation of Naphthionate and Pyranine relative to ^{18}O. Yotsukura et al (1970, quoted by Smart and Laidlaw, 1977) reported adsorption of Rhodamine B onto glass sample bottles, probably due to its cationic nature. The sorption of Rhodamine WT has been shown to increase from solutions of methanol and acetone in batch and column experiments (Soerens and Sabatini, 1992) and may affect similar dye compounds. This is an important consideration when choosing tracers for use at groundwater sites contaminated with solvents.

Dyes are also affected by temperature, salinity, pH, background fluorescence and turbidity (Feuerstein & Selleck, 1963). Fluorescence varies inversely with temperature, the amount of variation depends on the dye. Fluorescence decreases with decreasing pH below about pH 7 as the structure of the dye molecule changes. The rate of decrease depends on the dye and the ions in solution. Pyranine is noted as being most suitable for tracing in acid pH ranges (Kass, 1994). The fluorescence of Pyranine changes with pH being green in neutral or alkaline conditions and blue in acid or alcoholic aqueous solutions (Benischke & Schmerlaib, 1986). The fluorescence of Rhodamine dyes is reduced with increasing salinity, but Fluorescein is not affected. Natural background fluorescence is caused mainly by dissolved organic carbon. Suspended sediment in samples can also raise the apparent level of background fluorescence. Orange dyes have much lower background levels than blue dyes. Green dyes tend to have the highest background readings (Smart and Laidlaw, 1977). The background levels affect the detectability of the tracer. Photochemical decay rates are high for some dyes - particularly Pyranine, Fluorescein and Photine CU. Fluorescent dyes degrade in the presence of hydrocarbons, but can still give useful results (Nahold and Hotzl, 1992).

Diffusion and dispersion of dyes is also important. The diffusion coefficient of Fluorescein is about one order of magnitude lower than chloride or bromide, which means diffusion is less important for Fluorescein during longer tests than for these ionic tracers (Zahn and Behrens, 1992).

Among the orange and green fluorescent dyes sodium fluorescein (Uranine), Rhodamine, and Pyranine have been used extensively.

Optical brighteners are a group of blue fluorescent dyes used as fabric whitening agents for paper and textiles and in detergents. They are therefore relatively cheap and their toxicology is well documented. Their widespread use has resulted in their appearance in the environment so background monitoring is essential. Optical brighteners fluoresce and are detected like fluorescent dyes using a fluorometer or passive detectors. Optical brighteners are photo degradable, and decay rapidly in light at a rate about four times that of fluorescein. Dilute solutions decay the most rapidly. This is not important for the tracer while in the groundwater, but the tracer and any samples collected must be stored in the dark. When using optical brighteners as tracers care must be taken that samples do not come into contact with any substances treated with optical brighteners such as cotton wool or paper and that fluorescent laboratory detergents are not used. Medical quality cotton wool forms a good passive detector for these dyes.

Optical brighteners are, like other fluorescent tracers, affected by pH, temperature, adsorption and photochemical decay. Adsorption of optical brighteners is greatest in the presence of organic materials. Experiments with photine CU have shown negligible decrease in fluorescence with increasing salinity. However the fluorescence is affected by the presence of iron and copper and optical brighteners may be of limited use in iron rich groundwater (Smart, 1976).

The optical brighteners, tinopal CBS-X and Leucophor BCF were used in a number of surface and groundwater tests in Italian alluvial, volcanic and carbonate aquifers (Uggeri & Vigna, 1997) where their use is accepted by the authorities for use in groundwater used for public water supply. Tinopal CBS-X was found to have a high retention in the matrix of fine grained aquifers and this, coupled with its low solubility was a drawback. The main problems with Leucophor BCF were its relatively high limit of detection and its high photosensitivity which meant that all injections into surface water were made in the dark.

The optical brightener Photein CU has been used for tracing in the Chalk aquifer (Ward et al, 1997) to prove connections between boreholes and give approximate groundwater velocities.

The toxicity of fluorescent dyes has been the subject of some discussion in the literature (Smart, 1976, Smart and Laidlaw, 1977; Leibundgut and Hadi, 1997; Anon, 1977). The use of tracers should not affect the groundwater environment and when there is a possibility of human consumption of the labelled water further precautions must be taken. Rhodamine tracers, particularly Rhodamine B, have been shown to be toxic to fish. Sulphorhodamine and Rhodamine B have also shown ill effects during laboratory tests on animals. At the concentrations used during tracer experiments fluorescent tracers are unlikely to cause danger to aquatic life but Leibundgut and Hadi (1997) recommend that the use of Rhodamine tracers be restricted. A review of studies on the toxicology of optical brighteners concluded that there is no toxic hazard to man even at excessive dosages (Akamatsu and Matsuo, 1973 quoted by Smart and Laidlaw, 1977). Tables 3.3 and 3.4 are taken from Leibengut and Hadi (1997) and give the results of recent work carried out in Germany. In their conclusions they state:

> "… Consideration of the results obtained for the different fluorescent tracers leads to the conclusion that most of the tracers can be considered harmless in the concentrations normally found in tracer experiments. Under normal field applications these concentrations are transient because of rapid dilution following injection. Nevertheless, the use of the rhodamine group should be limited and restricted to exceptional cases. Although the maximum tracer concentrations of 10 mg/m^3 for groundwater and 100 mg/m^3 for surface water are below the levels of toxicological relevance, it is recommended that for hydrological aims dye concentrations should be maintained as far below those values as possible. ….."

Table 3.3 **Results from in-vitro tests for the genotoxic potential of hydrological tracers and the assessment of their applicability in ground water (UBA, 1966).**

Tracer	*In-Vitro Tests*		*Applicability in groundwater*
	Salmonella/ microsomes-test	*Cytogenic analysis*	
Uranine	negative	negative	OK
Sulforhodamine B	negative	negative	OK
Amidorhodamine G	negative	negative	OK
Rhodamine WT	negative	positive	Questionable
Rhodamine B	----------	positive	Questionable
Pyranine	negative	negative	OK
Na-Naphtionate	negative	negative	OK
Tinopal CBS-X	negative	negative	OK
Tinopal ABP	negative	positive	Questionable

Table 3.4 **LD_{50} values of several hydrological fluorescent dyes (cf. Kass 1992)**

Tracer	*LD_{50} (mg/kg)*	*Tested animal*	*Reference*
Uranine	4740	mouse, oral	Smart (1982)
	300	mouse, i.v.	Smart (1982)
Eosine	>1000	rat, oral	Smart (1982)
	550	mouse, i.v.	Lutty (1978)
Rhodamine B	89.5	rat. I.v.	Webb et al (1961)
	120	rat, i.p.	Rochat et al (1978)
	95	mouse, i.p.	Rochat et al (1978)
	890	mouse, oral	Rochat et al (1978)
Sulforhodamine B	>10000	rat, oral	Smart (1982)
Amidorhodamine G	>10000	rat, oral	Smart (1982)
Rhodamine WT	>25000	rat, oral	Smart (1982)
	430	mouse, i.v.	Lutty (1978)
Pyranine	>5000	rat, oral	Bayer-Sicherheitsblatt (1983)
	1050	mouse, i.v.	Lutty (1978)
Amidoflavin FF-PW	8524	rat, oral	Hoechst - data sheet
Lissamine	8560	rat, oral	Smart (1982)
	110	mouse, i.v.	Lutty (1978)
Tinopal CBS-X	7800	mouse, oral	Ciba-Geigy - data sheet
Triazine-stilbene	7000	mouse, oral	Akamatsu & Matsuo (1973)

i.v. is intravenous injection: i.p. is intraperitoneal injection

3.2.4 *Gases*

Dissolved stable gases are a relatively new type of groundwater tracer. They are generally non reactive and non toxic. They have advantages over conventional ionic tracers in that there are smaller density changes associated with the gas dissolving. Gases are non polar molecules and should not react with aquifer materials during transport, unlike ionic tracers which are involved in substitution reactions. Gas tracers are usually analysed by gas chromatography and the detection range can be as much as seven orders of magnitude from solubility to detection limit. Gas volatility can cause problems with preparing and injecting labelled water to the aquifer.

Sulphur hexafluoride (SF_6) is a volatile inorganic gas. Column experiments using sandy materials indicate that SF_6 behaves similarly to bromide (Wilson & Mackay, 1993, 1996). SF_6 may be slightly retarded in aquifer materials with high organic carbon contents.

The noble gases (Davis et al, 1985) are non reactive and non toxic. However the heavier noble gases do sorb to some extent on clay and organic matter (Davis et al, 1985). They are naturally present in groundwater in low concentrations. Variations in the concentration ratios of different noble gases are a function of surface temperatures at time of recharge. Some noble gases such as helium and krypton have been artificially introduced as groundwater tracers.

Helium (Carter et al, 1959) - expensive analysis. A ^{4}He tracer used by Eikenberg et al (1992) compared well with ^{82}Br and sodium fluorescein tracers. As helium partitions strongly into the gas phase, it was concluded there was no evidence for unsaturated zones within the test zone. Laboratory and field tracer experiments using helium dissolved in water were conducted by Gupta et al (1994). Laboratory tests showed that helium exhibited little retardation with respect to specific electrical conductivity in saturated media and could be used as a suitable tracer there, but that helium was not an effective tracer in unsaturated media. The field tests showed similar results to tracer work with NaBr. The helium can be introduced to the injection well by injecting water saturated with helium or by bubbling helium into the water in the well.

Krypton has been successfully used in the United States as a tracer in natural gradient tests in sand and fractured bedrock aquifers. Krypton was bubbled into the injection well and samples collected using an in-line sampler. After four months Krypton was still detected in an unconfined aquifer indicating its suitability for use in low flow conditions.

Deuterium is a useful way of labelling some organic compounds. Deuterated organic compounds were used to trace the movement of a BTEX contaminated plume of anoxic groundwater (Davis et al, 1992) to determine rates of biodegradation and contaminant retardation.

Chlorofluorocarbons (CFCs) have also been used as gas tracers using methods similar to that of the noble gases. Care must be taken in sampling and analysis that the samples do not come into contact with any plastics or grease to which they are strongly adsorbed. CFCs are also used as indicators of modern recharge as discussed in Section 3.2.8.

3.2.5 *Isotopes*

Isotopes, both stable and unstable, are potentially a very useful group of groundwater tracers. However they often require specialist sampling techniques and the analysis is usually expensive. For some isotopes, analysis may only be available in a few laboratories worldwide and large volumes of sample may be required.

A review of stable isotopes is given by Gat (1971) and Davis et al (1985). Stable isotopes are generally used as environmental isotopes although they may also be artificially introduced for specialist studies.

Radioactive nuclides of a number of elements have the potential to form useful tracers for groundwater investigations. However generally the costs are high, public acceptability is low and safety considerations are paramount. Radionuclides with short half lives are good for use in repeat tests. It is the chemical nature of the element or compound which determines the characteristics of the tracer so effects like adsorption and ion exchange must still be taken into consideration. Radiation hazards have prevented most work with radioactive tracers. The IAEA has set maximum admissible concentrations in potable water for radionuclides (Gaspar, 1987). These give limits to their utilisation in field experiments.

It has been suggested that tritium is the most ideal groundwater tracer as it can be part of the water molecule and therefore behaves essentially the same as normal water. Tritium has a half life of 12.3 years and belongs to the lowest radio-toxicity class. It emits beta radiation which makes it more difficult to detect in the field than radioisotopes which emit gamma radiation. Tritium has been used as an artificial tracer but background levels of tritium have also been used as an environmental tracer (see Section 3.2.8).

I^{131} and Br^{82} have been successfully used in groundwater investigations (Knutsson, 1968; Hulla et al, 1992). Their half lives are quite short (8 days and 36 hours respectively) which makes them more suitable for tracer work in karstic areas than in intergranular aquifers. Experimental work shows that Br^{82} is more suited to work in materials with a high organic content as I^{131} is adsorbed significantly.

Metal complexes containing radionuclides have also been utilised. In particular colbalt cyanide ($K_3Co(CN)_6$) containing Co^{60} or Co^{58} and the chromium EDTA complex (Cr-EDTA) containing Cr^{51} have proved useful (Knutsson, 1968). Co^{60}-EDTA complexes can also be used. The performance of such complexes is dependent on the environmental conditions, particularly the type and amount of clay present (Gaspar, 1987). For example Co^{60}-EDTA cannot be used in basic conditions and where a large proportion of clay is saturated with Na^+ or Ca^{2+}.

3.2.6 *Temperature*

Water temperature has not been used frequently but has the potential to be a useful tracer. The high specific heat capacity of water means that it changes temperature only slowly as it migrates. However changes in water temperature alter density and viscosity which affect velocity and flow direction. Small temperature contrasts, and therefore accurate temperature measurement, are required to reduce the impact of convection (Davis et al, 1980).

Water temperature has been used to detect the movement of artificially recharged water and seepage of water from pipes (Keys & Brown, 1978, Armbruster et al, 1992). Water temperature tracing can also be useful to detect river recharge to an aquifer (Davis et al, 1985) or springs in the bed of a river. Seasonal temperature fluctuations in the river water can be detected in recharged water while the groundwater temperature remains fairly constant.

3.2.7 *Microbiological*

Microbiological tracers can be used to determine movement of particulates in groundwater. Their use has been reviewed in the literature (Keswick et al, 1982, Harvey, 1997). In the past microbiological tracers were used to study groundwater flow, particularly in karstic and fractured aquifers. More recently they have been used to predict the transport of pathogenic organisms in a variety of aquifer types. The suitability of any particular micro-organism to mimic the transport of a pathogen depends on its surface chemical, physical and physiological characteristics. The aquifer characteristics play an important part in determining whether a micro-organism will be retarded, immobilised or be confined to particular flow paths due to its size (Harvey, 1997). In addition micro-organisms may grow in situ or fall prey to protozoa.

All microbiological tracers are sensitive to environmental stresses such as temperature fluctuations, UV and agitation but these are minimised in groundwater conditions. Microbiological tracers have a finite lifetime and it is therefore important to know the die off time for any microbiological tracer used. The introduction of these tracers does not pollute the aquifer as only a small mass of biological matter is introduced and this will degrade. Detection limits for microbiological tracers can be very small.

Microbiological tracers cover a large size range (Table 3.5). In addition their morphology is very diverse. They can be spherical, rod shaped, with or without a tail or other appendages, and with or without filaments.

Bacteria may be used for tracer studies, providing care is exercised over the choice of organism since they may be potential pathogens. Strains which can be distinguished from organisms occurring naturally in the aquifer, for example those resistant to antibiotics or producing H_2S, must be utilised. However care must be taken with antibiotic resistance strains as the antibiotic resistance can be transferred to potential human pathogens in the aquifer. Some bacteria will grow in the aquifer environment giving spurious results, others adsorb to the substrate. The size and shape of the organism may also affect its transport. Bacteria probably do not adequately mimic the transport of other micro-organisms such as viruses. Bacteria can be cultured in large quantities and are easy to detect using light microscopy or plating on selective media. Strains of *Escherichia coli* and *Baccillus stearothermophilus* were used by Sinton (1979, 1980) to trace in groundwater in New Zealand. Indigenous bacteria were collected, concentrated, stained with a fluorescent marker and reintroduced to an aquifer by Harvey et al (1989)

Table 3.5 Size ranges of different microbiological tracers compared with other particulate tracers

	Size Range	Reference
Virus	0.2-1.0 µm	Davis et al, 1985
Bacteriophage	45-230 nm	Rossi et al, 1994
Bacteria	1-10 µm	Davis et al, 1985
Yeast	2-3 µm	Davis et al, 1985
Lycopodium spores	30 µm	

The use of human enteric viruses as tracers is restricted as many of them are pathogenic. However vaccine strains of viruses such as Poliovirus Type 1 LSc have been used as tracers. These can still cause disease and must be used with extreme caution if at all. Animal enteric viruses do not usually infect man and viruses such as Bovine Enterovirus Type 1 have been used as tracers. However the use of bacteriophage is to be preferred over mammalian virus in almost all circumstances.

Bacteriophage are viruses whose hosts are specific bacteria. They cannot replicate outside the host. They are non pathogenic to humans and animals and have no environmental effects. Phage are often adsorbed onto aquifer material due to their negative charge. Differences in the adsorption and/or movement of phage is due to differences in their surface characteristics (Bricelj & Misic, 1997). Bacteriophage degrade with time, but their half lives are generally measured in weeks (e.g. Rossi, 1992). Temperature and pH are the main factors affecting decay rate, but as aquifer temperature and pH is usually fairly constant these are not perceived to be important in groundwater studies. Some phages are rendered inactive by aeration and agitation (Bricelj and Sisko, 1992). Different phages can be used in the same test or to repeat tests because the hosts are specific. Samples are analysed on a plate of the host organism and the number of plaques formed as the host is killed are counted. Phages can be concentrated from large volumes such that it is possible to detect 1 phage in 20 litres of water (5×10^{-5} pfu/ml, pfu = plaque-forming unit).

Early work with phage was carried out in rivers (Wimpenny et al, 1972) using an *E coli* bacteriophage. Rossi et al (1994) found that bacteriophage could travel more than three times faster than the fluorescent tracer, Naphthionate. Recent work funded by the Environment Agency (D. Chadha, pers comm.) showed that fish were not affected by the presence of bacteriophage in a 96 day trial.

3.2.8 *Environmental tracers*

Environmental tracers are those tracers which have been introduced to the environment by natural or anthropogenic processes. They can act as tracers of flowpaths in aquifers and may be used to determine groundwater age. As any pumped water is likely to be a mixture of waters with different flowpaths and therefore different travel times since recharge the concept of a single groundwater “age” is not entirely valid. A summary of environmental tracers with respect to the Chalk aquifer is given by Darling (1996).

Tritium (^{3}H) is the radioactive isotope of hydrogen. High levels of tritium were introduced to the environment by thermonuclear activities in 1963-64. This results in a peak in the levels of tritium in groundwater dating from this time which have been used to study rates of groundwater movement in the unsaturated zone. Tritium studies in the unsaturated zone of the Chalk have downward velocities of 0.64 to 0.99 m a^{-1} (Smith et al, 1970, Smith and Richards, 1972, Foster, 1975, Foster and Smith-Carrington, 1980, Geake and Foster, 1989) with lower rates in the east of England, presumably due to lower rainfall (Darling, 1996). Tritium concentrations are usually measured in tritium units (TU) which is the number of tritium nuclei per 10^{18} stable hydrogen nuclei.

Variations in the stable isotopes of hydrogen (^{1}H and ^{2}H) and oxygen (^{16}O, ^{17}O and ^{18}O) have been widely used to study groundwater movement as they form part of the water molecule. They have been of particular use tracing large scale movement of groundwater and to locate areas of recharge (Davis et al, 1985).

In the absence of large altitude differences depletion in stable isotopes normally signifies recharge under colder conditions. Stable isotope studies in the Chalk of the London basin showed some depletion in O and H compared with the margins leading to the conclusion that the 'light' water in the centre of the basin contained a late-Pleistocene water component (Smith et al, 1976).

The other main stable isotopes utilised are nitrogen (^{14}N and ^{15}N), sulphur (^{32}S, ^{34}S and ^{36}S) and carbon (^{12}C and ^{13}C). Other isotopes such as ^{3}He (daughter of tritium decay), ^{36}Cl from thermonuclear testing, and noble gas isotopes have been proposed, but there are problems associated with the sampling of some and many of the isotopes are only analysed by a few specialist laboratories world-wide.

Radiocarbon (^{14}C) is widely studied. Although all ^{14}C is of atmospheric origin, measurements are difficult to interpret due to the problem of calculating the input from the rock. The amount in groundwater may be altered by biological processes and by exchange with non radioactive carbon. However ^{14}C is very useful in determining the approximate residence time of water from 500 to 30,000 years old. In the Chalk aquifer age interpretations from <10 ka to >25 ka have been suggested (Darling, 1996).

Chlorofluorocarbons (CFCs) are products used in the post war era as propellants and refrigerants. Concentrations of CFCs have risen linearly over the last 30 to 40 years. They are well mixed in the atmosphere and form a universal tracer of post war recharge. They are measured by gas chromatography which can be carried out in the laboratory or in the field. Studies have been carried out in the United States eg Busenberg and Plummer (1992). The distribution of CFCs is the subject of a current NERC PhD project at UEA which has shown that plumes of CFCs can be mapped (Atkinson pers comm, 1997). CFCs are detectable in low concentrations (1-100 ppt, by gas chromatography) and are poorly sorbed except in presence of organic material.

Agri-chemicals are chemical compounds used in the agricultural industry. Nitrate is commonly used as an indicator of agricultural pollution from fertilisers, but may be removed by denitrification processes. Pesticides are another group of agri-chemical which is likely to be more persistent in aquifers. Pesticides commonly adsorb to aquifer materials. Analysis for pesticides is sophisticated and therefore expensive.

3.3 Practicalities of tracer use

Safety is of paramount importance during any tracer test. The previous section reviews the toxicology of tracers with respect to the concentrations likely to occur during the test. The final concentrations of the tracer in the groundwater at sampling points may not be dangerous, but chemicals in a concentrated form may pose risks to personnel preparing or injecting tracers and the effects of tracers on the personnel conducting the test must be taken into account. In particular the COSHH regulations regarding any substance must be reviewed before using any chemical. The regulations do not name substances, but require a safety assessment to be made of all proposed uses of all substances, taking into account toxicity, likely exposure, likely type of exposure/ingestion and related hazards. Toxicity data, for the purposes of COSHH assessment is often provided by the manufacturers. It is a statutory requirement to carry out COSHH procedures on all new procedures involving chemicals and to prepare codes of practice if appropriate

Personnel handling dyes should wear protective gloves and clothing. Inhalation of dust should be avoided and a face mask used if necessary. Skin coming into contact with a dye should be washed immediately with soap and water. Splashes in the eyes should be washed with copious quantities of water (Smart, 1984).

3.4 Tracer Database

There are many different types of tracer available for use in tracing groundwater, and the choice of which tracer to use is not always clear. Although there is a large amount of information available about the various materials which can be used as tracers, much of this information has hitherto been scattered around the literature. As part of this project, an attempt has been made to compile this data into a useful and usable form.

The information presented in the database is compiled from the body of literature listed in the references of this document. There are gaps in some fields in the database as some information is not readily available. A full listing of the data presently saved in the various Tables of the database is given in Appendix E.

3.4.1 *Database structure*

The tracer database is a relational database comprising a number of tables which contain details of various tracers in separate fields. The table **Name** is the primary table, containing the tracer id (by which the related tables are linked), tracer name and tracer type. The tracers are then split into tables according to their type: (Water temperature), **Particle**, **Microorganism**, **Ion**, **Dye**, **Stable Isotope**, **Radioisotope**, **Gas** and **Fluorocarbon**. The first fields in all these tables are the tracer id and tracer name. Details of the other fields in the tables are described below (where the field name is self explanatory or has been described earlier no description is given).

Particle

size	The size of many particulate tracers is a constraint on the types of aquifers in which they can be used.
effective distance	Reference is made to the distance travelled by the tracer during examples of its use.
use	Some particulate tracers may be particularly suitable for certain tracing parameters.
aquifer medium	Some particulate tracers are only suitable for tracing in karstic media.
concentration needed	The large size of some particulate tracers and their consequent loss may necessitate a large initial concentration.
background level	
detection method	
adsorption	Some particulate tracers may be adsorbed onto the aquifer.
environmental effects	
cost	
comments	

Microorganism

Although microbial tracers could be considered a type of particulate tracer, they have been detailed in a separate table. Example of virus and bacteriophage tracers have been given, but the list is not comprehensive.

size	
effective distance	Reference is made to the distance travelled by the tracer during examples of its use.
use	Some particulate tracers may be particularly suitable for certain tracing parameters.
background level	Some microorganisms naturally occur in groundwater.
detection method	
adsorption	The tendency for microorganisms to adsorbed onto the aquifer is indicated by the distribution coefficient, K_a.
die-off rate	The die-off rate of microorganisms may limit their use in long-term tests, but will also limit their environmental effects.
time required for assay	As microorganisms are detected by growing on nutrients, immediate quantification of results is not possible.
environmental effects	Some microorganisms may present a health hazard.
cost	
comments	

Ion

Tracers in this table have been detailed as either individual ions or as the ionic compounds. Some parameters in the table may only be appropriate for the ion (eg diffusion coefficient?) or for the compound (eg solubility).

chemical formula:	This includes the charge on the ion where appropriate.

background level:	Most ions are naturally present in groundwaters. An indication of the concentrations expected is given.
solubility	This is only given for compounds
sorption	Cations tend to be adsorbed onto clays (and organic matter?); adsorption is lower for anions.
analytical methods:	Most ions can be measured by a variety of methods. The key is in the table **Key**
detection limit:	This may vary according to the detection method used.
diffusion coefficient	
interaction with aquifer	As well as adsorbtion onto clays and ion exchange, other processes may occur which retard the ions.
environmental/health: effects	

Dye

colour index:	The colour index is the standard reference to dyes. Most dyes are classified according to their chemical structure (the CI Constitution Number) and according to the dyeing method for which they are used (the CI Generic Name).
chemical formula:	There are some disagreements in the literature about the chemical formula of certain dyes.
molecular weight:	This depends on the chemical composition.
background level:	Natural waters often contain organic matter which may contain acids with fluorescent properties. Suspended sediment can raise apparent background fluorescence because of light absorption and scattering by the sediment particles. Background fluorescence will vary according to the aquifer. Smart & Laidlaw (1977) suggest that fluorescence in a karstic limestone aquifer is higher at the blue and green wavelengths than orange. Background levels of optical brighteners are increasing in surface and groundwaters due to industrial pollution, and should be measured before starting a tracer test.
detection limit:	Varying figures have been found for this in the literature. This may be due to advances in detection techniques.
max excitation wavelength:	The wavelength at which light is absorbed by the dye.
max emission wavelength:	The wavelength of light which is emitted by the dye as fluorescence.
solubility	
sorption tendency:	Dyes can become adsorbed to clays or organic matter within the aquifer medium. Dye adsorption is controlled by factors such as temperature, pH, water quality and dye concentration. An indication of the sorption tendency can be given by the distribution coefficient, K_d or the _rd. The sorption tendency is particularly pertinent when tracer tests in soils are being considered.
photochemical instability	Some dyes decompose in the presence of light due to oxidation and other chemical changes. However, this tendency is not of major importance for groundwater tracing.
effect of pH:	Low pH affects the chemical form of the dyes which reduces their fluorescence. Most dyes are stable within the pH range found in natural groundwaters.
environmental/health effects	Various investigations on the toxicity of dyes are documented by Smart &: Laidlaw (1977). The toxicity of a substance can be indicated by LD50, the dose for which 50% of the animal population died, or LC50, the long-term concentration which resulted in the death of 50% of the animal population studied. Most dyes do not appear to pose serious toxicity problems at the concentrations used, except Rhodamine B, which is more toxic than other dyes owing to its cationic form. The optical brighteners present a very low toxic hazard even at excessive dosage levels.

commercial form:	Many dyes are in powder form; some are sold in solution due to their low solubility.
manufacturer:	Fluorescent dyes are manufactured commercially.

Stable Isotope

source	Most stable isotopes used in tracing are naturally occurring.
use	
sampling method	
analysis	

Radioisotope

half life	The half life of an isotope may determine its suitable use.
source	Many radioisotopes used for groundwater tracing were introduced by bomb testing; others are naturally occurring. Introduction of radioisotopes into aquifers for groundwater tracing is unlikely to occur due to potential health implications.
radiation types	Radiation emitted may be alpha, beta or gamma.
particle energy	The main energy of the radiation emission.
detection method	Gamma radiation can be detected *in situ*.
detection limit	Detection of radiation is usually sensitive.
"age" range	Radioisotopes which have a particular anthropogenic source may have a particular age range for which they can be used as groundwater tracers. This may also depend on half life.
use	

Gas

background	
solubility	
retardation	
use	
detection method	
detection limit	

Fluorocarbon

chemical formula	
boiling point	
solubility in water	
environmental effects	
analysis	

3.5 Commonly used tracers

In this section information has been presented about a large number of substances which may be used in groundwater tracer experiments. Further information is presented in Appendix E: Database of tracers. However, in general the choice of tracer will be limited for a variety of reasons and a summary is produced here of the information available about the tracers most commonly used in the UK. These are the fluorescent dyes Fluorescein (Uranine) and Rhodamine WT, the optical brightener Photine CU, and a bacteriophage. The data reported here are obtained from the published literature.

Rhodamine WT

colour index	CI Acid Red 388
chemical formula	$C_{29}H_{29}N_2O_5Na$
molecular weight	508
background level	variable
detection limit	0.006 μg/l
max excitation wavelength	554 nm
max emission wavelength	572 nm
sorption tendency	Medium, low in Chalk. Sorbs to activated charcoal, which can be used as a passive sampling method
photochemical instability	very low
effect of pH	fluorescence affected below pH5
environmental/health effects	LD_{50}>25 g/kg (rat); possibly carcinogenic; possibly non-mutagenic; LC>320 mg/l (rainbow trout)
commercial form	20% solution
manufacturer	Crompton and Knowles Ltd Waterside Industrial Park, Smiths Road Bolton BL3 2QJ Tel: 01204 363644

At present (1998) Rhodamine WT costs £29.30/ kg.

Photine CU

colour index	CI Fluorescent Brightener 15
background level	variable, high in industrial or domestic effluent
detection limit	0.36 μg/l
max excitation wavelength	345 nm
max emission wavelength	435(455) nm
sorption tendency	low in Chalk. Sorbs well to unbleached cotton wool which can be used as a passive detector
photochemical instability	high; k=0.064
effect of pH	fluorescence affected below pH 6.5
environmental/health effects	low toxicity
commercial form	20% solution in urea, with ethanolamine
manufacturer	Clariant Calverley Lane Horsforth Leeds LS18 4RP Tel.: 0113 258 4646

It costs 75p per kilo and is sold in 25 kg batches.

Uranine (Sodium Fluorescein)

colour index	CI 45350; Acid Yellow 73
chemical formula	$C_{20}H_{10}O_5Na_2$
molecular weight	376
background level	variable - some naturally occurring organic matter fluoresces at similar wavelength
detection limit	depends on instrument and background: 0.002-0.01 μg/l
max excitation wavelength	491 nm
max emission wavelength	514 nm
solubility	25 g/l, 500 g/l @ 80°C
sorption tendency	tends to sorb to Chalk
photochemical instability	high
effect of pH	fluorescence affected below pH6.5; max intensity >pH9
environmental/health effects	not toxic to goldfish or crucians, non-carcinogenic, non-mutagenic
commercial form	powder; aqueous solution
manufacturer	Holliday Dyes and Chemicals PO Box 22 Huddersfield HD2 1UH

Bacteriophage T7 (host: *E.Coli* B)

size	head 60 nm, tail 17 nm
use	Has been used in granular and fractured aquifers
background level	Not usually found
detection method	Cultured and then counted
adsorption	highly adsorbed on sand - more than 50% in 20 minutes (other bacteriophage not so highly sorbed)
die-off rate	half life of ~ 1 year
time required for assay	24-48 hours
environmental effects	Believed to be harmless
cost/supplier	Suppliers of bacteriophage include several Water Companies (e.g. Yorkshire, Thames). Suppliers usually provide the phage and the analysis as an inclusive service.

Theses four tracers are most commonly used in groundwater studies because of their availability, suitability for resolving particular issues as well as experience and familiarity of use as tracers. This familiarity should not preclude the use of other tracers if they appear to be more applicable. However, lack of experience and uncertainty may necessitate additional basic research into the properties of some tracers before they are widely used. In particular the sorptive characteristics and the background levels should be determined for each aquifer/tracer combination.

4. TYPES OF TRACER TEST

Tracer test methods are numerous ranging from the very simple to the very complicated where sophisticated automated monitoring equipment is used. The scale of the tests can range from less than one metre (e.g. laboratory and column experiments) through to tens and hundreds of metres (e.g. radial tracer tests) and thousands of metres (e.g. natural gradient tests). The tests can involve just small samples of aquifer material taken to the laboratory, single boreholes, springs, sink-holes, multiple boreholes, or any combination of these.

Applications of tracer testing are regularly reported in the literature for addressing hydrogeological and broader environmental problems. In general, standard techniques and concepts are applied after modification to address specific problems. Examples of the application of tracer tests in the subsurface to determine properties or parameters which are not directly related to aquifer properties and contaminant transport in aquifers include the use of tracers for detecting cross contamination within a monitoring well (Meiri, 1989) and the use of tracers to test the integrity of landfill liners (Shackelford et al, 1989). Use of tracer testing and the development of tracer test methods will continue to increase with greater knowledge and experience and the realisation that it provides an applied method for investigating and solving a wide range of problems.

This chapter will outline some of the most commonly used methods in hydrogeology which are employed to improve basic understanding of groundwater flow parameters (e.g. velocity, connection and direction) and contaminant transport (e.g. travel time, dilution, dispersivity) in major aquifers. For more detailed information about application of tracer testing for solving specific problems numerous publications are available. A starting point is the proceedings of the International Symposium on Water Tracing. There are now seven proceedings volumes the latest published in 1997 (Kranjc, 1997). Throughout this chapter, the methods are illustrated by examples of their application (see boxes).

4.1. Methods not requiring boreholes

4.1.1. *Laboratory scale tracer tests*

Laboratory tests on aquifer material can be used to provide preliminary and relatively rapid information on tracer behaviour. Samples of aquifer material can be packed into columns and an artificial 'groundwater' flow regime established through the column. The flow can then be spiked with a tracer or contaminant and its migration through the column monitored (e.g. Williams and Higgo, 1994), Figure 4.1. This method has both advantages and disadvantages in that whilst being relatively rapid, the packing of materials in columns does not reflect natural *in situ* conditions and so the results are hard to relate to the larger scale natural situation. These tests do allow tracer behaviour to be examined in particular aquifer environments, e.g. sorption, reaction etc.

An alternative, is to take a block of aquifer material (which may contain a fracture) and place it in a specially designed testing rig which allows the sample to remain saturated and have flow induced through it. Again the flow can be spiked and progress of the tracer monitored (e.g. Greswell, 1995), Figure 4.2.

4.1.2. *Field scale tracer tests*

Field tracing techniques which do not use wells and boreholes require the use of natural or artificial recharge and discharge features such as sink holes, quarry floors, springs, drains and the base of landfills. The presence of these features provide access to the groundwater and so can be used for

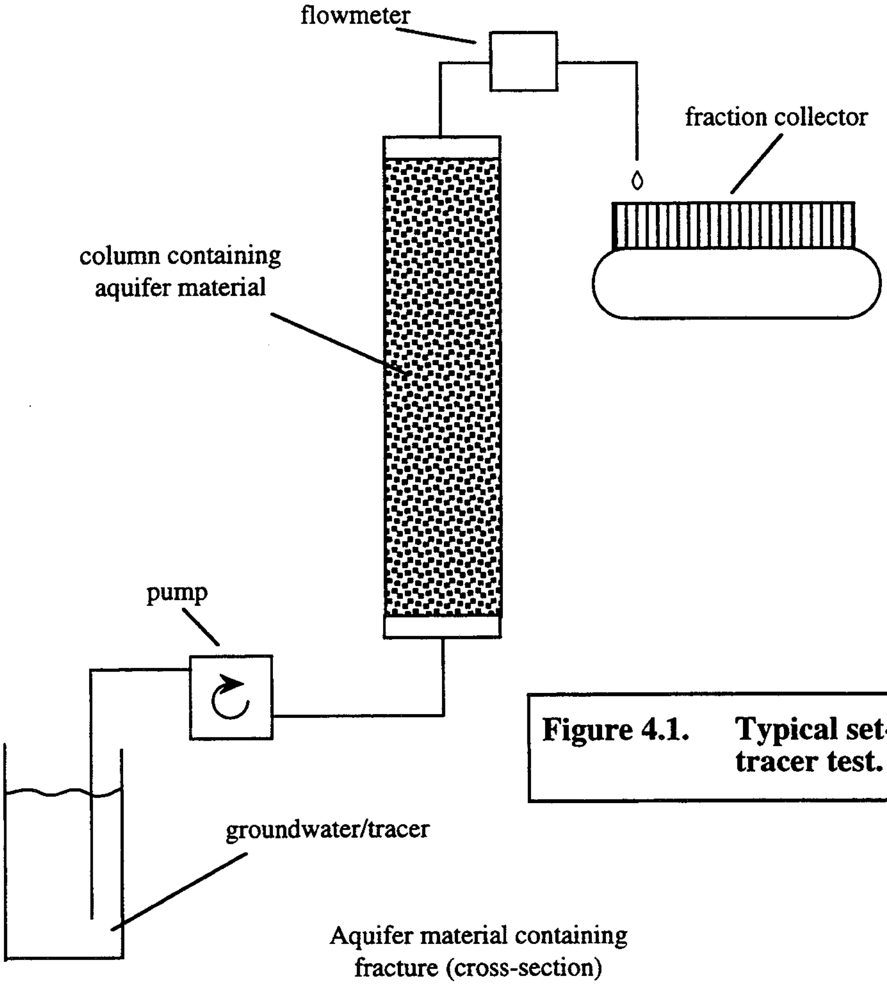


Figure 4.1. **Typical set-up of laboratory column tracer test.**

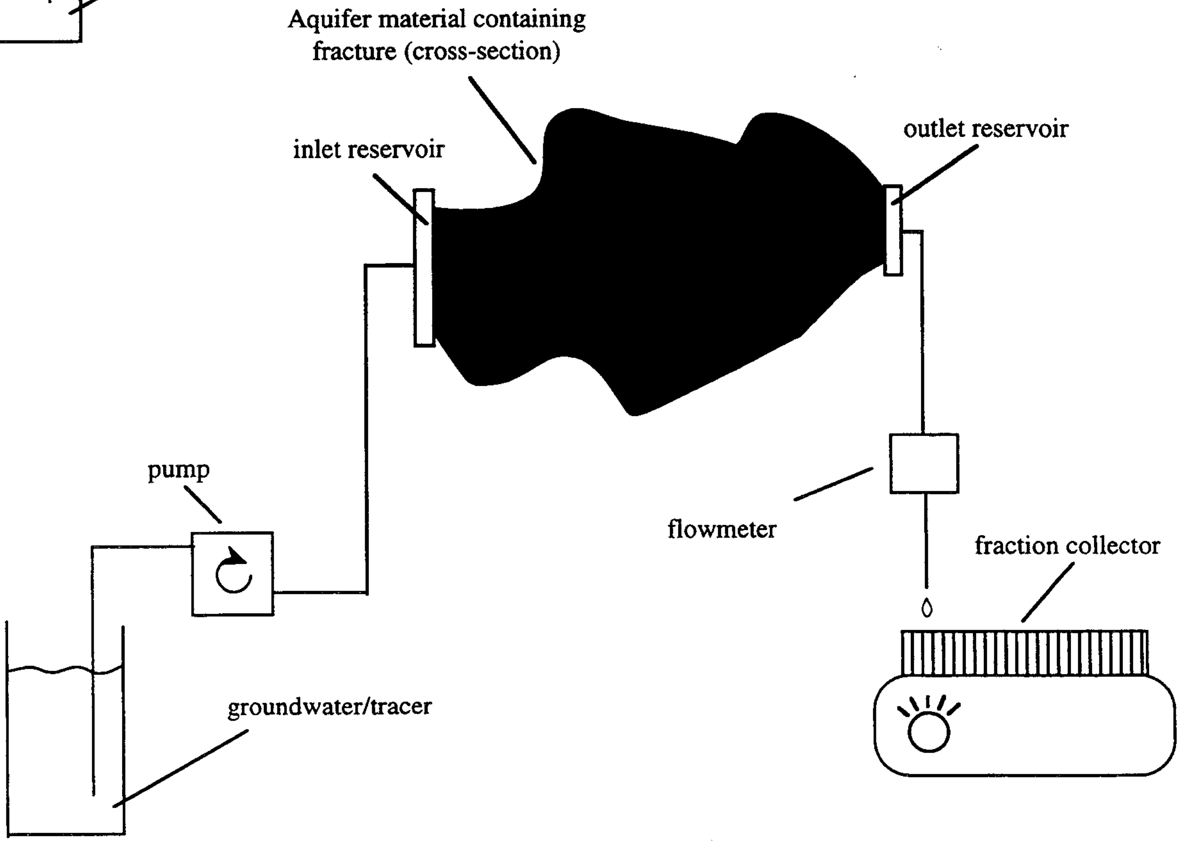


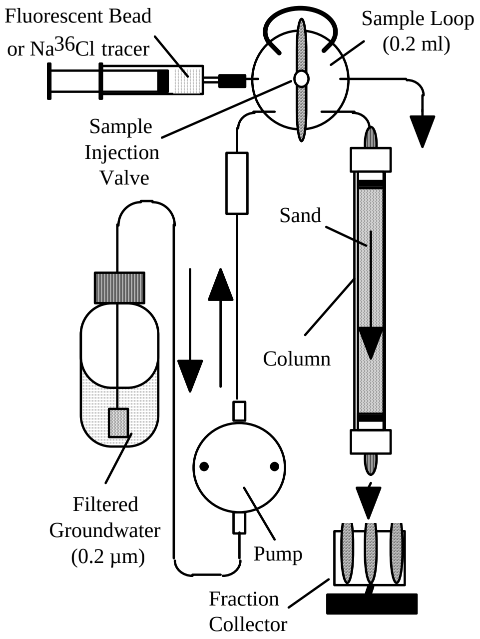
Figure 4.2. **Tracer test arrangement for laboratory scale fracture tracer test**

injecting tracers (recharge points) or sampling (discharge points). The flow systems being investigated are usually under natural conditions, i.e. there is no artificial control on the flow. Background knowledge of the aquifer system and hydraulic gradients is essential if this type of test is to succeed.

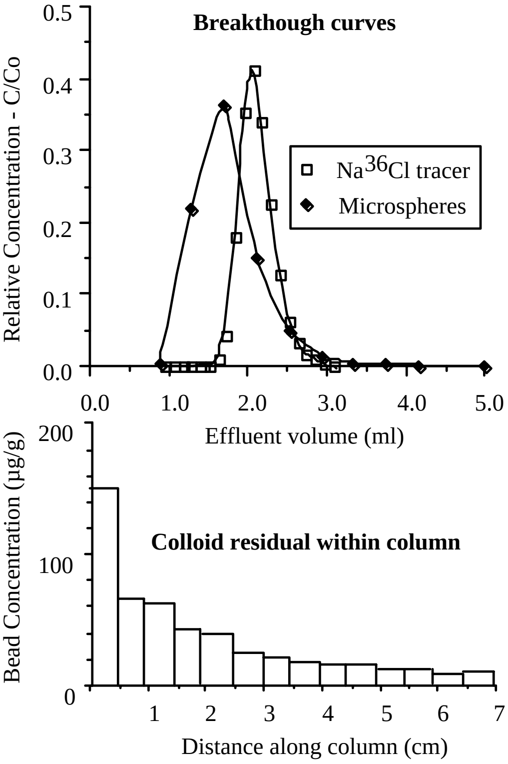
Box 4.1 Migration through glacial sand: Role of colloids in radionuclide migration. (Harrison, 1996 and Ward et al, 1997)

Steady-state circulation of native groundwater through a 6.5 cm long x 1.0 cm diameter glass column packed with saturated glacial sand was established. A conservative tracer (0.2 ml of $Na^{36}Cl$) and fluorescent microspheres (colloids) (0.2 ml of 0.25% w/v 0.05 µm microspheres) were injected on to the column. Once complete breakthrough curves had been obtained, the flow through the column was stopped and the column material (core) extruded and the solid quantitatively analysed to establish the distribution of the residual microspheres (Figure 2).

The breakthrough curve shows that the mean travel time of microspheres is shorter than for the solute tracer. This is due to the microspheres being transported only through pore spaces with apertures larger than 0.05 µm. These preferential flow paths also have the highest velocities. The solute tracer flows through the full pore volume. The residual distribution of microspheres indicates the proportion adsorbed and/or filtered.



Apparatus for column experiments.



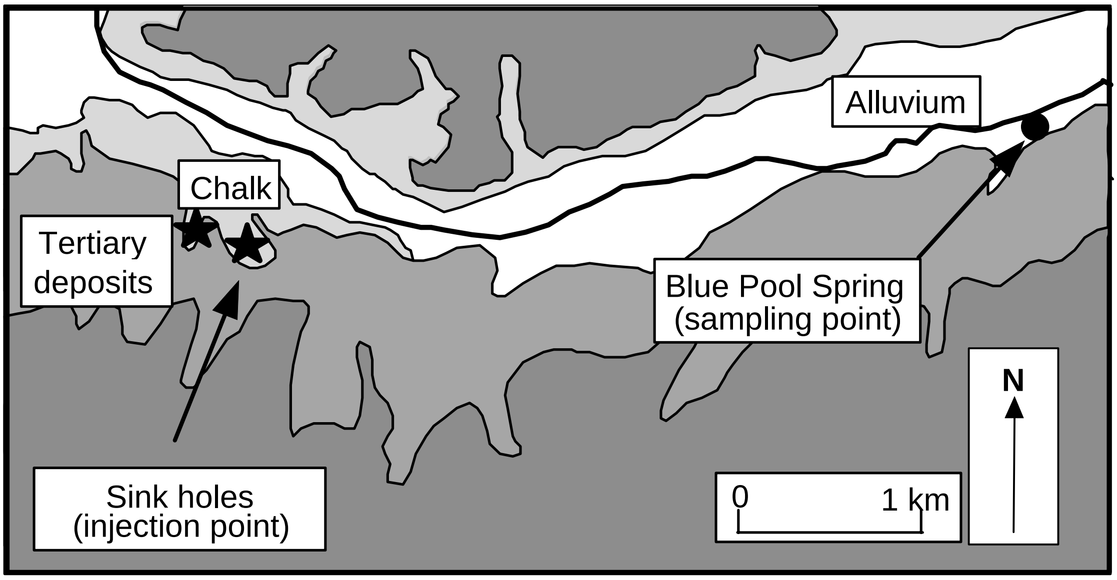
The scale at which these tests are performed is variable and depends very much on the distribution of injection and sampling points. However, in general, these types of experiments are classified as large scale tests because of the often large distances between injection and sampling points and the large volume of aquifer involved.

The purpose of this type of test is usually to allow determination of flow paths, groundwater velocities (travel times), dilution and dispersion, definition of recharge catchments or separation of groundwater flow components (Nativ et al, 1997). The results can be used to predict the impact of surface spill incidents (Price et al, 1989), long term releases of contaminants from drains and landfills (Hobson, 1993) and to define recharge catchments (Smart, 1976).

This type of test is more commonly applied in fractured media such as chalk and limestone where transport over large distances is possible over relatively short time scales and has been used more than any other type of test. There is an extensive literature on application in karstic environments around the world. In major fractured aquifers in the UK such as the Chalk and the Lincolnshire Limestone the method has also been applied, but less widely (Atkinson and Smith, 1974, Price et al, 1992 and Banks et al, 1995).

Box 4.2 The Chalk as a karstic aquifer: evidence from a tracer test (Banks et al, 1995)

High groundwater velocities in the Chalk in the region of the Chalk/Tertiary boundary are believed to be associated with the development of karstic features. These are demonstrated at the surface by features such as swallow holes and dolines. Traditionally these features have been used for disposal of road run-off and agricultural waste. Pollution of down gradient springs by surface run-off from agricultural areas indicated that contaminated water was entering the sub-surface and travelling through the aquifer with very limited attenuation of pollutants. A fluorescent dye tracer (fluorescein) was injected into a sinkhole, identified as a likely source of the pollution, by pouring 4 litres of the concentrated tracer into the dry swallow hole and flushing with a large volume (1000 litres) of water. Water at the spring was sampled by automatic water sampler at a frequency of 1.5 hours. Tracer was detected after approximately 16.5 hours with concentration peaking after 19.5 hours. This indicated groundwater velocities of between 6.8 and 5.8 km/day between the sink hole and spring. Analysis of the results yielded an estimate of hydraulic conductivity of 20 m/s and fissure aperture of 5.4 - 5.9 mm.



The application of this type of test is less common in poorly fractured aquifers, e.g. sandstones, where fracture flow is less dominant regionally. In these cases, this type of test should probably be restricted to small scale experiments or experiments where continuous injection of tracer can be maintained with long term monitoring.

4.2. Methods requiring boreholes

Where boreholes are present or can be drilled, a wider range of tracer test methods are available. The boreholes can be used singly (single borehole tests), in pairs, in large numbers (multi-well tests) or in combination with the features described in the previous section.

Boreholes can be used for natural gradient tests or installed with pumps to allow induced gradient tests. The latter allows greater control on the experiments, increases the likelihood of detection and broadens the capability of tracer testing

The methods most commonly used and which are most applicable are described in the following sections.

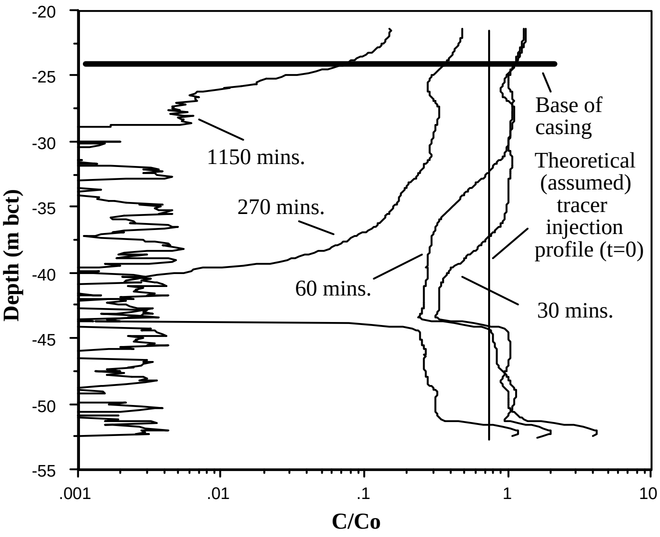
4.2.1. *Single well techniques*

Natural gradient tests

Natural gradient tracer tests involve the introduction of a tracer into the whole or part of the borehole column without causing any disturbance in natural hydraulic conditions, e.g. head change, density change etc. The movement and/or dilution of the tracer by the local groundwater flow regime is then monitored, again without disturbing the natural flow.

Box 4.3 Single borehole dilution tests to identify flow horizons and tracer injection points (Ward, 1997)

To identify and quantify major flow horizons within a Chalk borehole in East Yorkshire as part of the planning stage for a large scale tracer test a series of single borehole dilution tests were performed. In one test, 8.8 litres of 250 g/l NaCl solution were injected into a 20 mm internal diameter hose lowered down the 52.5 m deep, 200 mm diameter borehole. The rest water level was at 21.5 m below casing top (bct) and base of casing was at 23.5 m. The injection was performed using the method described in Appendix A. Before installation of the hose and periodically after injection, the borehole was logged using a portable electrical conductivity/temperature probe. This provided a corrected conductivity profile down the borehole and with each log, a pattern of dilution. Dilution within the borehole was very rapid with conductivity, in the uncased part of the borehole, returning to background within 20 hours. A single major flow horizon/zone between 41 - 44 m bct dominated flow in the borehole and the aquifer locally. Analysis of the results indicated a Darcy velocity of 3 x 10^{-5} m/s (2.8 m/day) and, assuming kinematic porosity equal to 0.01, a groundwater velocity of 3 x 10^{-3} m/s (280 m/day) associated with this feature. The flow zone between 41 - 44 m bct was therefore selected as tracer injection point for the large scale test.



Horizontal specific discharge and, under favourable conditions, flow direction can be determined by the single borehole dilution method. This involves injecting a tracer into the whole saturated borehole column or packered interval so that a column of tracer of uniform concentration is obtained. The subsequent dilution of the tracer is then monitored by means of an in-situ detector or by carefully sampling the borehole (without minimal disturbance to the natural hydraulic conditions).

Dilution of the tracer should be exponential with a time constant related to the specific discharge. Calculation of water velocity can then be made if kinematic porosity is known. The model used for analysis of single borehole dilution tests is presented in Appendix B.9.

In fractured aquifers, the dilution in the borehole may be dominated by a single fracture. In this case using a kinematic porosity for the whole aquifer thickness may be inappropriate and lead to overestimates of the groundwater velocity. In the case where a single fracture is responsible for the dilution profile at a point a kinematic porosity value of one may be more representative.

A number of assumption are made when analysing the results including that good initial mixing is achievable, there is an even initial vertical concentration distribution and no (or very little) vertical flow is present.

To determine direction of flow, a multi-directional or orientated sampler is required.

Where vertical flow occurs, i.e. in deep boreholes penetrating more than one hydrogeological unit or where head variations occur within the aquifer, the single borehole dilution analysis model is invalid. Therefore, alternative test methods should be considered. For example, packers may be used to isolate sections of the borehole or if a new borehole is to be drilled, a multiple completion should be considered.

Even if neither of these or other alternatives are possible, the single borehole dilution test can still provide useful information. It can indicate where inflows and outflows occur within the borehole, a valuable requirement for any further point-to-point tracer testing and also under favourable conditions provide an indication of vertical head gradients. Vertical head gradients can also be determined by injecting a tracer at a single point within the borehole e.g. near the base or at the top or injecting a combination of tracers at different depths. Monitoring their distribution(s) with time within the borehole can provide detailed information on vertical flow rates and hydraulically active horizons within the borehole. A further variant of the single borehole dilution test is to continuously circulate the tracer in the borehole after injection. This will result in a loss of vertical detail but can provide a value for the average flow rate.

Drift and pump back tests

This single borehole method combines the affects of natural flow and artificially induced flow. It involves the injection of a tracer into the borehole in the same way as for the single borehole dilution test.

The injected tracer is then allowed to leave the borehole and enter the aquifer, migrating with the natural groundwater flow for some measured period of time. This may be hours, days or even weeks. After this time, the tracer is pumped back towards the injection well and its concentration over time measured.

The concentration/time profile (breakthrough curve) resulting can then be used to determine linear ground water velocity, effective porosity and dispersion characteristics if hydraulic conductivity of the aquifer is known. Ideally therefore, this method should be used in conjunction with a pumping test. The flow rate used for recovery of the tracer must be sufficient to overcome the natural hydraulic gradient but not so great that definition of the breakthrough curve is lost. Selection of suitable flow rate may be difficult unless knowledge of the natural gradient and hydraulic conductivity is already available.

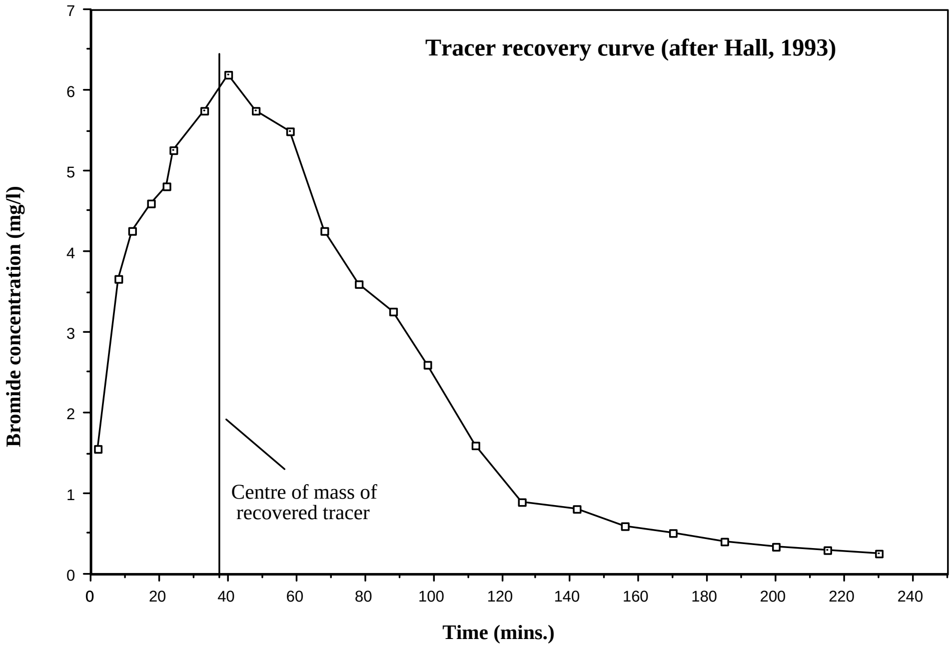
The equations for determining velocity and kinematic porosity from the drift and pump back test can be written (Leap and Kaplan, 1988):

$$V = \frac{1}{t_i}\sqrt{\frac{Qt_p}{\pi n_e b}} \qquad (4.2)$$

where, V = average linear groundwater velocity, Q = the pumping rate, t_p = the time since start of pumping to recover half of the injected mass of tracer, n_e= kinematic porosity, b = aquifer thickness and t_i = the time elapsed since the injection of tracer to recover half of the injected mass of tracer.

Box 4.4 Single well tracer tests in aquifer characterisation (Hall, 1993).

A drift and pump back test was used for determining kinematic porosity and groundwater velocity in unconsolidated alluvial sands and gravels. The boreholes tested were 254 mm screened wells 25 - 27 m deep with a rest water level at approximately 15 m below ground level (bgl). Tracer was injected by suspending a weighted hose in the borehole with the lower end close to the base. 125 g of lithium bromide (LiBr) was dissolved in 2.2 litres of water (the internal volume of the hose below the water table) and poured down the injection hose. To inject the tracer, the hose was slowly withdrawn from the borehole. Following injection, the bromide concentration in the borehole was monitored as function of time and depth to examine the dilution profile. Down hole measurements were made at 0.9 m intervals using a submersible ion-selective electrode. After just over 2 days, the borehole was pumped at 327 m^3/day and the bromide concentration of the abstracted water measured. The breakthrough curve shows that half the mass of the recovered tracer was recovered after 50.6 minutes which yielded a kinematic porosity of between 0.16 - 0.21 and Darcy velocity of between 0.6 - 0.7 m/day (7 - 8 x 10^{-6} m/s).



If the hydraulic conductivity, K, is known from hydraulic testing and the local hydraulic gradient, I, has been determined then the above equation can be combined with Darcy's equation:

$$v_d = Vn_e = -KI \qquad (4.3)$$

to give the following equations for velocity and kinematic porosity:

$$V = \frac{Q_t}{\pi b t_i^2 KI} \tag{4.4}$$

$$n_e = \frac{\pi b K^2 I^2 t_i^2}{Qt} \tag{4.5}$$

Alternatively, if the dilution of the tracer in the borehole is monitored, a value for v_d can be obtained as described for the borehole dilution test. This can be used to determine the magnitude of the hydraulic gradient, if K is known.

The above equations assume that there is no sorption or retardation of tracer and that flow is radially symmetrical. Where a significant natural gradient exists, radial symmetry is unlikely to be maintained. The assumptions underlying this method are that flow is radial and that there is no retardation of tracer resulting from adsorption or other processes. Additionally it is assumed that the local hydraulic gradient is constant and the aquifer is homogeneous. Although the tracer enters only a small volume of aquifer (down-gradient of the well), the assumption of radial symmetry during the pump back stage is important in order that equations 4.2 - 4.5 are applicable.

Variations of this method include the injection of a known volume of tracer into the borehole followed by water to force the tracer in to the aquifer. After some time, injection is stopped and the borehole pumped (Fried, 1975 and Noy and Holmes, 1986). Interpretation of this type of test can also provide values of longitudinal dispersivity.

The disadvantages of the drift and pump back test are that there may be problems injecting the tracer into a borehole which is already equipped with a pump and the length of time that is required between tracer injection and pump back may be difficult to estimate.

4.2.2. *Multi-well techniques*

Multi-well techniques comprise the use of two or more boreholes for groundwater tracing experiments. In general the techniques consist of injecting tracer instantaneously or continuously in to one or more boreholes and monitoring arrival and concentration at one or more additional boreholes down gradient. The gradient may be either natural or artificial.

The presence of boreholes can provide information at a range of scales but are probably most effective at the intermediate scale between the large scale natural gradient tests and single borehole tests. Depending upon the borehole configuration, scale of investigation can range from just a few metres (Sen et al, 1989) to several kilometres (Ward and Williams, 1995) depending on the nature of the aquifer being studied.

Natural gradient

Natural gradient tests require boreholes to be positioned along the line of flow (down gradient) or within the region in which dispersion of the tracer occurs. Experiments using boreholes for natural gradient tests therefore require a good knowledge of the flow regime within the aquifer. Unless boreholes can be installed specifically for the tracer tests, suitable configurations are often not available.

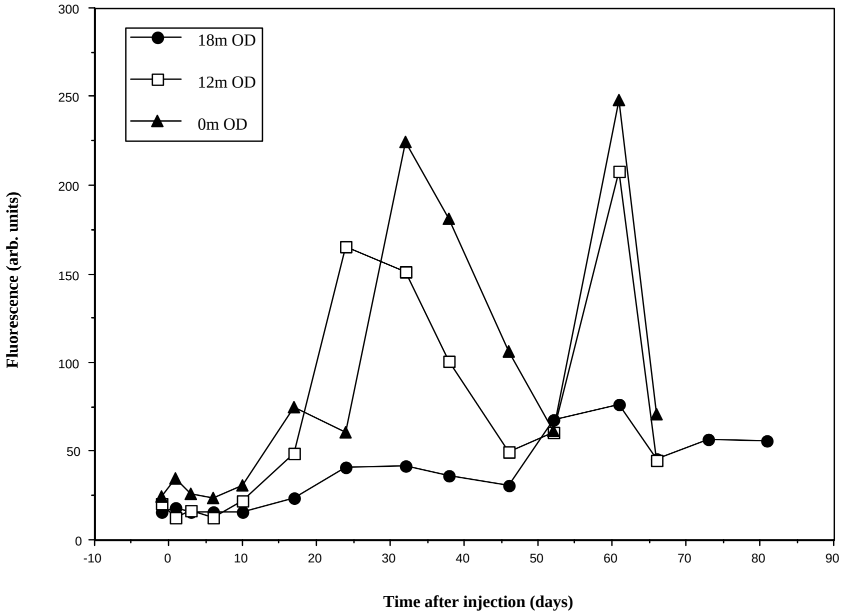
Where boreholes can be installed, it is advantageous to install more than one sampling or injection borehole. For example, a configuration which has a series of satellite sampling boreholes surrounding a central injection well could be installed or, if groundwater flow direction is known, a series of sampling boreholes could be installed at different distances down gradient (Sudicky et al, 1983, LeBlanc et al, 1991 and Ptak and Teutsch, 1994), Figure 4.3.

The parameters which can be determined from natural gradient tracer tests between boreholes include travel time, linear groundwater velocity, longitudinal and lateral dispersivity. Kinematic porosity can also be determined if combined with results from single borehole testing which can be run simultaneously.

The advantages of natural gradient borehole tests are that they do not require sophisticated equipment if suitable boreholes already exist and because natural conditions prevail, the tracer has the opportunity to interact with the aquifer.

Box 4.5 Natural gradient tracer test, Kilham, Yorkshire (Ward and Williams, 1995).

Two natural gradient tracer tests between boreholes have been performed to determine groundwater flow connections and velocities in the floors of two dry valleys in the Chalk of East Yorkshire. Tracers (fluorescein and photine CU) were injected into two observation boreholes in the upper reaches of the dry valleys and passive samplers were used to monitor for arrival of tracer in five boreholes down gradient of the injection sites. These sampling sites were up to 3100 m from the injection points. Geophysical logs were used to identify active flow zones within the monitoring boreholes and the locations at which the passive detectors should be placed. Up to three passive samplers (activated charcoal bags and cotton wool) were placed in each borehole. 5 kg of Photine (as a 20% solution) and 9 kg of fluorescein were injected via hoses into each of the injection boreholes at positions adjacent to the major flow horizons. Passive samplers were collected and replaced -7, -1, +1, +2, +4, +7 days before/after injection and then weekly for 90 days. The cotton wool was analysed under a UV lamp for detection of Photine CU (an optical brightener) and the charcoal was analysed by flurometer after firstly desorbing any tracer using a solution of ammonium hydroxide in propan-1-ol. Groundwater velocities of between 50 - 280 m/day were measured along the valley floors.



The disadvantages are that if there are insufficient boreholes or they are wrongly positioned, the tracer will not be detected. Even over long distances, the lateral spread of tracer can be very small but if it is detected there is no guarantee that the borehole has intersected the axis of the plume. In fractured media, the effective fracture network along which the tracer is moving may not be

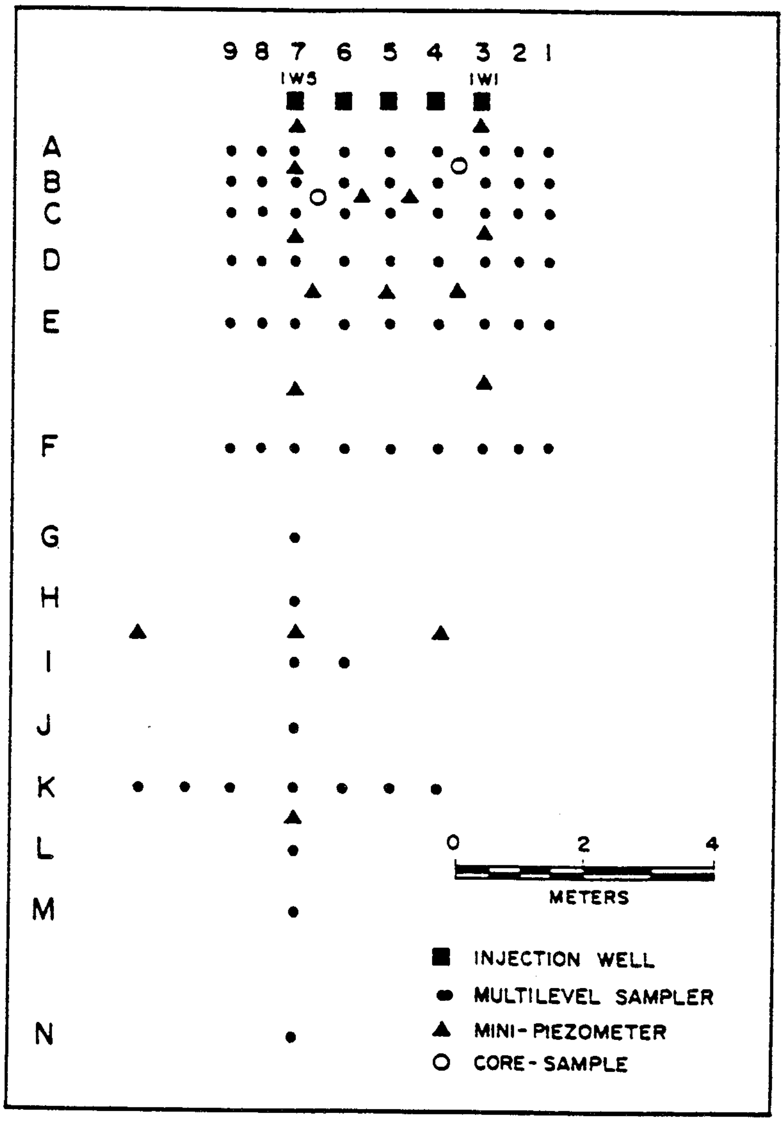


Figure 4.3. Example of natural gradient tracer test borehole array at Borden, Canada (from Sudicky et al., 1983).

intersected by the sampling borehole even if it is directly down gradient. The only solution is therefore to install large numbers of monitoring points which is usually prohibitively expensive.

Another disadvantage is the length of time for the tests. Whilst in fractured media travel times can be rapid (Ward and Williams, 1995 and Ward et al., 1997), in porous media travel times will be very long and dilution through dispersion, large.

Forced gradient - radially converging flow

Forced gradient tests involve imposing an artificial hydraulic gradient, i.e. by pumping in or out of the aquifer, to overcome the natural gradient. The application of a forced gradient improves the likelihood of tracer recovery because the flow within the aquifer can be better controlled. Tracers are introduced into the aquifer within the zone influenced by the imposed gradient. A critical comparison between natural gradient and forced gradient tests, for determining aquifer and transport properties, made by Gaillard et al (1987) suggests that there is good agreement between the two approaches.

The simplest forced gradient tests involve the use of two wells, a pumped well and an observation/injection borehole penetrating the same formation. This configuration is commonly available where boreholes have been drilled for aquifer testing and abstraction (Ivanovitch and Smith, 1978, Kachi, 1987 and Ward, 1989).

Box 4.6 Radially converging tracer tests to determine fissure aperture, dispersivity and matrix diffusion (Lloyd et al, 1996).

A series of well controlled tracer tests were undertaken in a purpose designed borehole array in the Lincolnshire Limestone. Their purpose was to examine this dual porosity aquifer to determine the controls on solute transport. Tracer injections were carried out in boreholes along two radii from a central pumping well at distances of 20 m and 40 m. The tracers used were fluorescein, amino-g-acid and bromide. Tracer injection was performed using two parallel weighted hoses suspended in the injection borehole with their lower ends close to the base of the borehole. The tracer was injected as a concentrated solution in a volume equivalent to the water-filled internal volume of the hoses. After withdrawal of the hoses, a circulation pump was operated to ensure continuous mixing of the tracer in the injection borehole. Small volume samples (5 ml) were collected for definition of the tracer injection pulse.

The discharge water from the central abstraction well was continuously sampled and analysed using a flow through cell attached to a fluorometer and ion-selective electrode. Sampling continued until groundwater concentrations had returned to background. The tests were operated by injecting the bromide (600 g of KBr in the 20 m boreholes and 1200 g in the 40 m boreholes) and measuring a crude breakthrough curve. The results of these tests were then used to refine the tests using the fluorescent tracers, optimise the sampling and produce more accurate and refined breakthrough curves. The quantities of fluorescein and amino-g-acid used were approximately 12 g and 32 g respectively. The breakthrough curves were analysed to determine dispersivity, matrix diffusion and fissure aperture. The value of matrix diffusion determined was far too high to be realistic, therefore it was concluded this parameter must represent a range of additional processes including channelling.

Test	Radius (m)	Q (m^3s^{-1})	Dispersivity (m)	Diffusion coeff (m^2s^{-1})	Fissure aperture (m)	Tracer and mass
1	20	5.17×10^{-3}	1.0	3.0×10^{-7}	0.024	Fluor. (12 g)
2	20	5.17×10^{-3}	3.0	0	0.06	AGA (34 g)
3	40	1.98×10^{-3}	1.0	1.1×10^{-5}	0.03	Fluor. (12 g)
4	40	1.98×10^{-3}	1.0	1.8×10^{-7}	0.03	AGA (31 g)

One of the wells is pumped at a constant discharge which results in radial converging flow around the well. The well is pumped to allow the cone of depression which develops to extend to or beyond the observation well which is used for tracer injection. Ideally time should be allowed for steady-state hydraulic conditions to be achieved.

The pumped water is sampled for the arrival of the tracer and the injection well for its disappearance. Coupled with analysis of the drawdown data (for determination of transmissivity and hydraulic conductivity), analysis of the tracer breakthrough curve(s) at the abstraction well can be used to determine longitudinal dispersivity, effective porosity, matrix diffusion, hydraulic conductivity and idealised fracture aperture and spacing of individual layers/fracture zones. Dilution data in the injection borehole can also yield velocities at this point, the shape of the input term which is required for interpretation of the breakthrough curves and the identity of the most hydraulically active horizons. This method is suitable from scales ranging from a few metres to several hundred metres in suitable aquifers. Experience has shown that common well configurations (an abstraction well and at least one fully penetrating observation borehole) are suitable for this type of tracer testing.

Whilst the simplest configuration of two wells can yield considerable information on aquifer properties, it cannot provide information on the heterogeneity and anisotropy of the system being studied. For example hydraulic conductivity may be greater in one direction than in another (Toynton 1979). Therefore where possible, additional satellite boreholes at different orientations and distances from the abstraction well should be constructed and used for simultaneous injection of different tracers or repeat testing (Figure 4.4).

Practical advantages of this type of test include the ability to control flow rates and there is only one sampling point (apart from the injection wells) which is easy to sample. Disadvantages are that there is a need to find a suitable and acceptable discharge point for the pumped groundwater which may contain elevated concentrations of tracer and the abstraction well needs to be equipped with a suitable pump, flowmeter and sampling arrangement.

Analysis of the results from radially-converging flow tracer tests is discussed in Chapter 7 and Appendix B.

Forced gradient - diverging radial flow

An alternative forced gradient method using the configuration of boreholes described in the previous section is to inject water in to the central borehole and establish a radially diverging flow field which is greater than the natural gradient. Tracer is then injected in to the central well as a pulse or as a continuous flow maintaining a constant inflow rate. The shape of the injection tracer pulse is monitored and observation boreholes sampled to monitor tracer breakthrough, (Ward, 1990).

For this type of test, more than one observation borehole is recommended because in heterogeneous formations, i.e. fractured media, the diverging flow may not be radial but may follow preferential flow paths which do not intersect the sampling point(s). Even in granular media, differences in arrival have been observed as a result of aquifer heterogeneity (Ward et al, 1990). At the very least, the monitoring borehole should be positioned down (natural) hydraulic gradient.

The disadvantages of this type of experiment generally outweigh the advantages unless the test is being performed at a very small scale and sufficient resources are available. Apart from the difficulties of locations of sampling boreholes, a continuous supply of water is required for injection, this water needs to be of the same chemical composition to avoid, chemical/biological reactions in the vicinity of the well screen which may reduce its efficiency for injecting water and so affect the hydraulics. Also, if the water level is near the surface, it may not be possible to achieve an adequate gradient to overcome the natural gradient. If multiple sampling boreholes are used, a much larger number of samples are required and this significantly increases the costs.

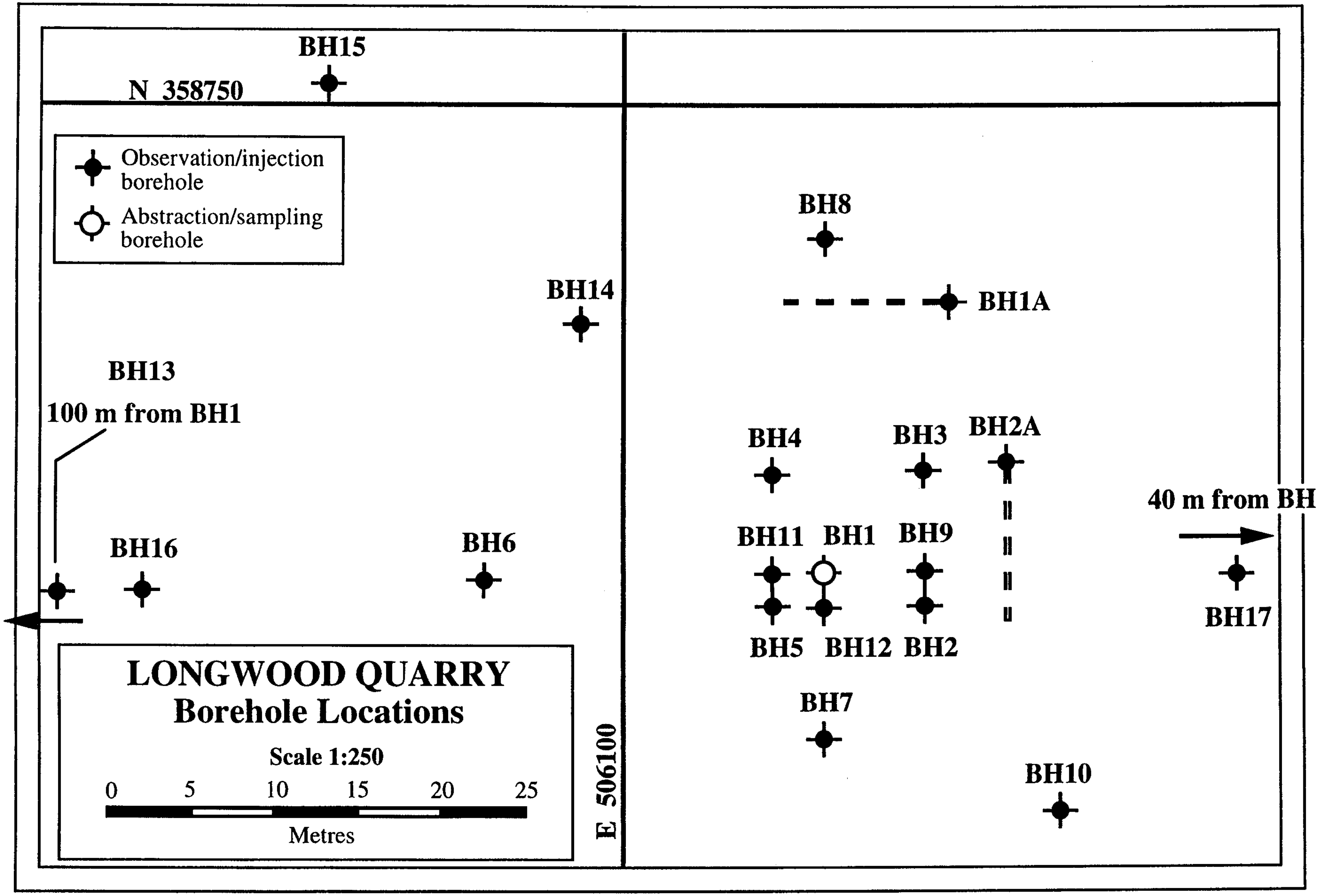


Figure 4.4 Complex array of boreholes allowing detailed monitoring and multiple tracer injections.

Forced gradient - dipole tests

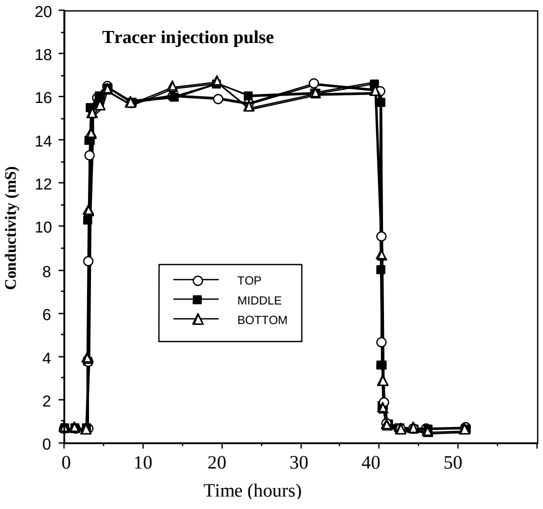
This method is effectively a combination of the two forced gradient methods above. A configuration with a minimum of two boreholes is used, with one used for continuous pumping and one for continuous injection of that water extracted at the same flow rate. This configuration is often referred to as a dipole system because of the flow field produced, Figure 4.5.

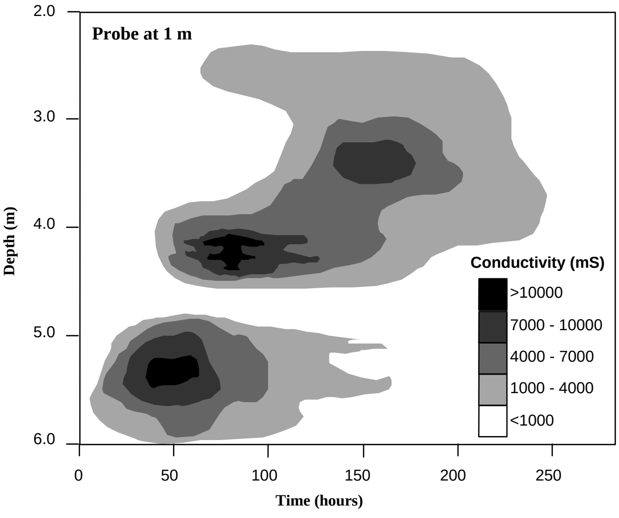
Once steady state flow conditions have been achieved, tracer is injected as a pulse or continuously in to the injection well without disturbing the established flow field. Monitoring the discharge of the extraction well produces the tracer breakthrough curve. An improved configuration is to use additional boreholes and monitoring points installed along the line between the two re-circulation boreholes, Figure 4.6 (Sen et al, 1991). If injection of tracer is into one of the monitoring boreholes (the one nearest to the water injection borehole), a simpler one-dimensional flow system can be assumed making interpretation much easier.

Box 4.7 Automatic monitoring of radial injection tracer tests using RESCAN (Ward et al, 1990).

A radial injection tracer test was carried out in an unconfined fluvial sand and gravel aquifer. Sodium chloride (NaCl) was used as an electrolyte tracer and breakthrough was monitored using resistivity probes installed in the ground. Six probes were placed at 1 and 2 m radii from a central, 6 m deep, fully screened, 150 mm diameter well along three limbs at 120° to one another. In addition, multi-level water samplers were installed adjacent to the resistivity probes for calibration purposes. The probes each had 80 electrodes along their length and allowed measurements at 5 cm vertical intervals.

Water was injected into the central well at flow rate of 4.5 l/min until steady-state conditions had been achieved. A step pulse of NaCl (5500 ppm) was then injected at the same flow rate over the whole saturated thickness of the aquifer. To ensure mixing, a re-circulation pump was installed in the central well. A total of 10 m^3 was injected, after which water injection was continued. The migration of the tracer pulse was monitored by the probes at 15 minute intervals. The detailed results enabled the heterogeneity of the formation to be studied in detail and the factors controlling solute migration identified. The experiment continued for 10 days.





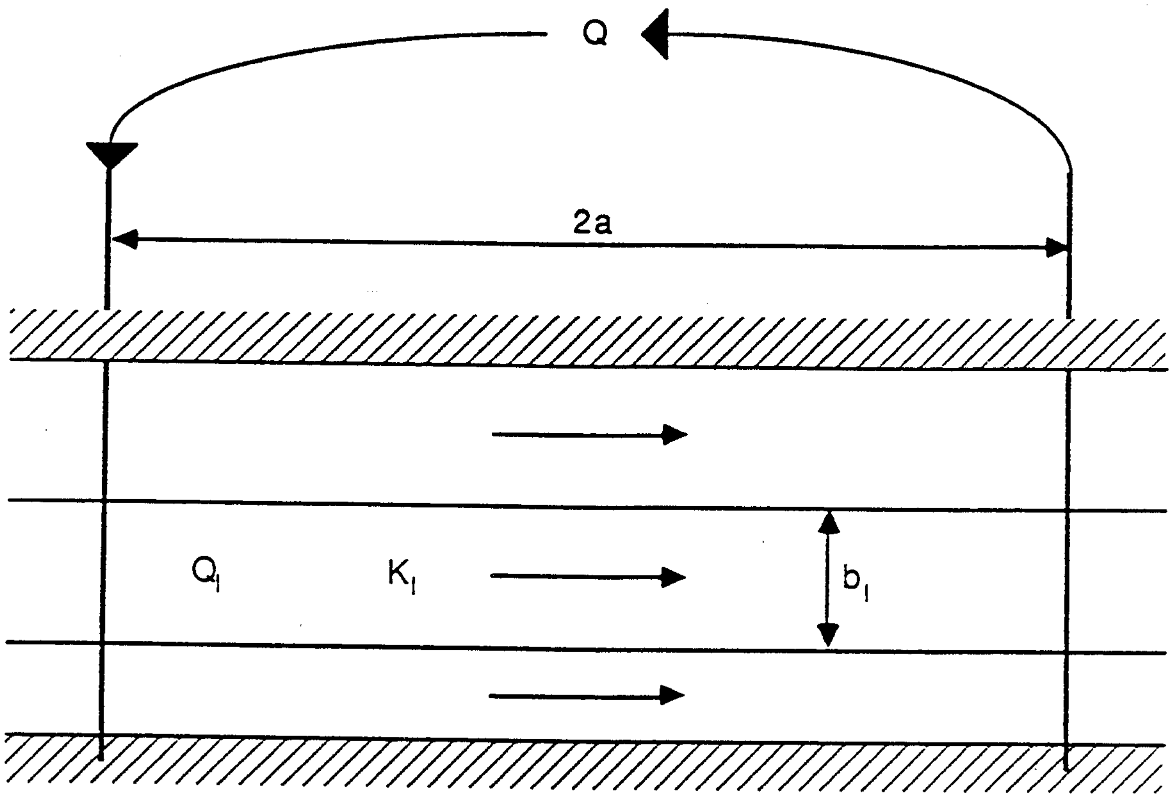


Figure 4.5. Simple dipole tracer test configuration

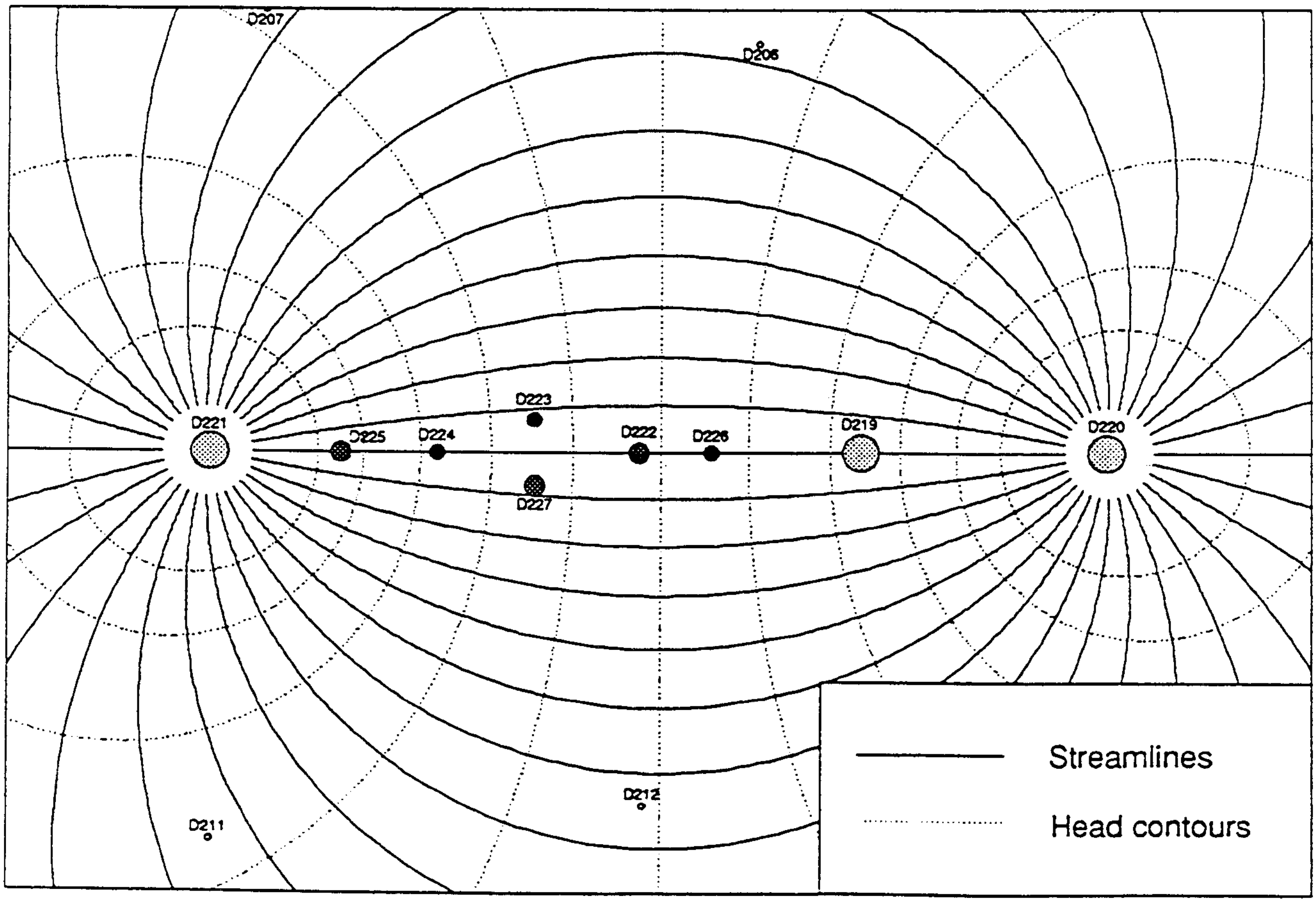
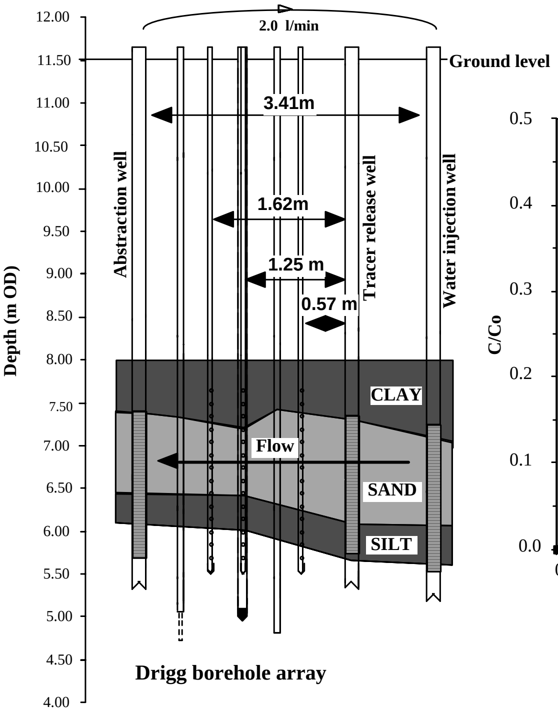


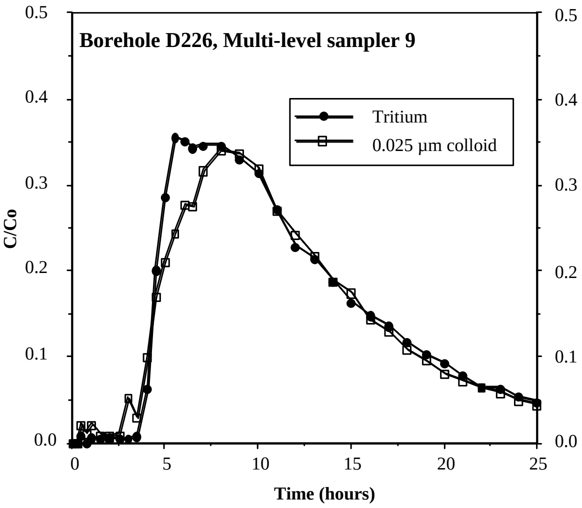
Figure 4.6. Drigg borehole array for dipole tracer array showing instrumentaion and flowlines.

The advantages of this type of tracer test are that water extracted is re-injected so there is no surplus to dispose of and the flow field is well defined. However, the distance between the outer boreholes should not be too large and blocking of the water injection borehole well screen by precipitates may occur causing an imbalance of flows.

Box 4.8 Forced gradient tracer tests at Drigg, Cumbria, UK (Williams and Higgo, 1994)

Tracer tests were carried out in a dipole borehole array to investigate the role of colloids in radionuclide migration. Groundwater was re-circulated between two borehole 3.41 m apart at a flow rate of 2.0 l/min. The boreholes penetrated an interbedded sand unit in a fluvio-glacial sequence. Colloidal tracers (including radio-labelled fulvic acid and polystyrene sulphonate, silica particles and fluorescent polystyrene microspheres) and a conservative tracer (tritium) were injected in a third in-line borehole 0.94m from the recharge well. Breakthrough curves were determined at two in-line multi-level samplers and one off-set by 0.125 m. Sophisticated instrumentation allowed extremely good control over the tracer injection which occurred over the full thickness of the sand unit and simultaneous sampling of multi-level samplers. The colloidal tracers ranged in size from 0.001 µm (fulvic acid) to 0.1 µm (fluorescent microspheres). The quantities of tracer injected were 17.5 MBq of ^{125}I-fulvic acid (0.5 g), 1660 g silica, 2.5 g fluorescent microsphere and 63 MBq ^{125}I-polystyrene sulphonate (3.09 g) and 37 MBq of tritium. The results showed that colloids were mobile and concentrations often peaked ahead of the conservative tracer demonstrating the differences in transport properties and the potential for more rapid transport of colloidal contaminants which were restricted to the larger aperture pore spaces.





4.3. Other methods

The foregoing sections have described some of the most commonly used methods in hydrogeology and the illustrations (examples described in the boxes) serve to demonstrate the application of these methods. In many cases, the method has been modified to achieve the objectives of the particular research project and in some cases combinations of methods used. The practitioner should not just be restricted to the methods which have been described but should use the methods as a basis for designing an appropriate programme of testing. It is quite likely that some modification of method will be necessary for testing in different geological environments.

Where new methods or applications are developed, the practitioner is encouraged to report these in the literature in order that an even broader portfolio of methods and experiences is available to hydrogeologists. Examination of the literature shows that tracer testing is becoming more widely used and reported (Kranjc, 1997).

5. PLANNING A TRACER TEST

The selection of a tracer test method, tracer(s), and procedures to adopt will depend very much on the hydrogeological problem to be solved and the information required. Before considering a tracer test it is recommended that all existing, available, data and influencing factors are considered before deciding on a course of action. It is possible that sufficient information already exists to adequately solve the problem without undertaking expensive and time consuming field work. For example, a tracer test may have already been performed or the other experimental methods such as hydraulic testing, water level monitoring, borehole geophysics or laboratory work etc. may be more appropriate. A procedure for tracer test selection and preliminary design is shown in Figure 5.1

If the need to perform a tracer test has been identified, it must be designed to answer as completely as possible the specific questions being asked. If important points are overlooked in planning a tracer test and the results of a long and expensive experiment can be at the very least ambiguous and possibly uninterpretable. It is therefore important that the purpose of the tracer test and the method chosen is clearly defined and understood and there has been adequate preliminary work.

This chapter aims to guide the reader in selecting a suitable tracer test method (once a need has been identified) and planning the test through a series of simple to follow tables, flow charts, decision trees and notes. The aim is to provide sufficient guidance for the professional scientist/engineer who has little experience of tracer testing. Chapter 6 will then proceed with general guidance on practical aspects during implementation of the testing and likely problems as well as discussing data requirements and reporting needs. Chapter 7 will describe analysis of tracer test data.

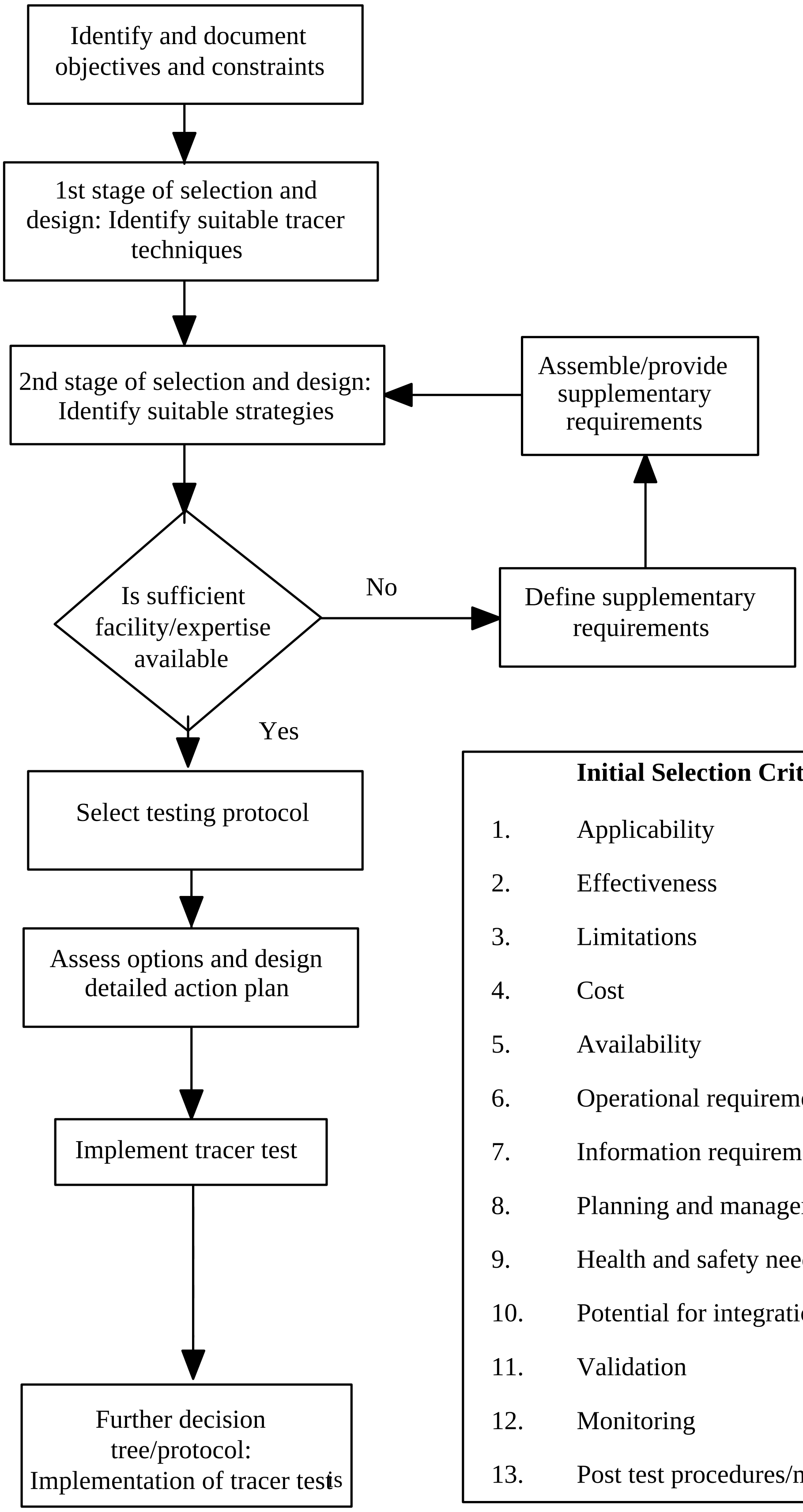
5.1. Preliminary data requirements

Hydrogeological, geological, geophysical and geochemical data should all be examined, as well as the practical and financial implications before identifying the need for a tracer test.

(a). **Hydrogeology**. Existing knowledge of the hydrogeology and aquifer properties of the area being studied is important. Data from pumping tests, water levels, distribution of aquifers, location of boreholes and their completion details, abstraction wells, springs, sink holes and recharge zones etc. should all be considered and analysed where appropriate.

(b). **Geology**. The geological setting of the study area should be established by considering borehole logs, the extent and distribution of geological units, presence of faults, fractures, fissure zones and zones of potentially enhanced permeability and as well as low permeability.

(c). **Geophysics**. Geophysical information can be used to supplement the geology and hydrogeology by providing characterisation of rock where geological logs and core material is not available. Borehole geophysical information can be used to infer geological structure, e.g. dip and lithology and identify potential continuity of horizons between boreholes, e.g. fracture zones. The data may also be used to indicate open fractures, natural flows and their local direction.



Initial Selection Criteria

1. Applicability
2. Effectiveness
3. Limitations
4. Cost
5. Availability
6. Operational requirements
7. Information requirements
8. Planning and management needs
9. Health and safety needs
10. Potential for integration
11. Validation
12. Monitoring
13. Post test procedures/management

Figure 5.1. Tracer test selection and design strategy

(d). Geochemistry. This is important because it may allow groundwater flow and behaviour to be established as a result of changes in chemical composition. These may result from water-rock interaction (e.g. movement of groundwater through a mineralised zone) or by release of potential contaminants into the ground (e.g. landfill leachate migration or addition of fertilisers and pesticides on the ground surface). Variations in groundwater chemistry can be used to establish the extent of a contaminant plume and distinguish between different groundwater facies as well as indicating the age of groundwater.

Consideration of the above will, under favourable conditions, provide a thorough basis for establishing what further information is required to achieve the objectives of the study without duplication of effort and without omitting important factors.

A conceptual model of the system being studied, at the required scale, should emerge from this initial data review. However, it may be established that further data are required to validate the model or clarify uncertainties. It is at this stage that a tracer test, amongst possibly other techniques, may be considered necessary to provide these data.

Once the decision to undertake a tracer test has been made, it is necessary to consider the options available for the given practical circumstances (time, finances and borehole configurations etc.) and the parameters to be measured. If considerable uncertainty exists about the flow system a phased approach should be employed. For example, preliminary small scale tracer tests can be performed before larger scale tests in order that the most economical use of time and resources can be made.

Selection of the tracer test method will depend on the problems to be solved and/or the information required and the availability of boreholes, sampling points etc. A series of tables are presented below to aid the selection of a suitable tracer test. Tables 5.1 provides guidance on the range of hydrogeological properties which may potentially be determined using the tracer test methods which were described in Chapter 4 and guidance on the complexity of data interpretation and analysis. Table 5.2 provides guidance on the properties which may be determined using existing environmental conditions/site facilities. The tables are self explanatory and should be used together with the tracer Test selection and design strategy (Figure 5.1)

5.2. Choice of tracer

Selection of an appropriate tracer for testing is very important and will depend on the scale of the experiment, its aims, natural background concentrations of selected tracer, analytical techniques, interaction with the aquifer, the experimental apparatus and (actual or potential) environmental impact. Ultimately the tracer should behave in an identical manner to the substance (water/contaminant) which is being traced.

Table 5.3 (adapted from Hobson, 1993) summarises the range of tracers available, some of the important properties which need to be considered during the selection process and the types of test for which they are suitable. More detail on the range of tracers available and their properties is given in Chapter 3. The most widely used tracers in UK aquifers are fluorescent dye tracers, optical brighteners and bacteriophage. When tracing to public water supply wells, bacteriophage are generally the most acceptable because they are non-toxic, colourless and chlorination de-activates them.

The appropriate authorities should be informed of the tracer test programme and permissions sought before starting (see Section 1.5). A proforma letter and recommendations for information which should be supplied are provided in Appendix A.

Table 5.1. Hydrogeological properties which may be measured using tracer tests.

Property to be determined	*Suitable test methods*	*Complexity of analysis*
Measurement of **flow paths**		
• connection between two or more points	3, 4, 6	A
• direction of flow	3, 4	A
Measurement of **velocities**		
• average linear water velocity	3, 4, 5, 6	B
• specific discharge/Darcy velocity	2	B
• contaminant migration velocity	3, 4, 6	C
Measurement of **aquifer properties**		
• hydraulic conductivity	2	D
• effective porosity	5	D
• heterogeneity	4	C
• fracture characterisation	4	E
• matrix diffusion	1, 6, 4	E
Measurement of **solute/contaminant transport properties**		
• dispersion	3, 4, 5, 6	E
• sorption	1, 4	E
• dilution	3, 4, 6	B
Measurement of **recharge/groundwater catchments**	3, 4	C
Measurement of **groundwater age**	3, 4	C

Key:

Test methods

1 - Laboratory tests (Section 4.1.1)
2 - Single borehole dilution (Section 4.2.1)
3 - Natural gradient tests (without boreholes) (Section 4.1.2)
4 - Natural gradient tests (multi-well) (Section 4.2.2)
5 - Drift and pump back (Section 4.2.1)
6 - Forced gradient (multi-well) (Section 4.2.2)

Ease of analysis

A - Easy, straight forward, generally qualitative.
B - Requires simple numerical calculation and basic understanding of hydrogeological concepts.
C - Requires an understanding of hydrogeological concepts and more advanced numerical calculation.
D - Application of standard numerical methods but requires significant hydrogeological expertise.
E - Requires application (and development) of complex mathematical methods by expert hydrogeologist/mathematical modeller.

Table 5.2 Potential test methods appropriate for existing conditions

Facilities/boreholes available	A	B	C	D	E	F
No field facilities (A)	1	-	-	-	-	-
Sink hole(s) (B)	-	-	3	4	4	4
Spring(s) (C)	-	3	-	4	4	4
Large diameter boreholes (D)	-	2,5,4	2,5,4	2,5	2,5,6	-
Piezometers (E)	-	2,5,4	2,5,4	2,5,6	2,5	-
Multiple boreholes (F)	-	2,4,5,6	2,4,5,6	-	-	2,4,5,6

Key:
1 - Laboratory tests (Section 4.1.1)
2 - Single borehole dilution (Section 4.2.1)
3 - Natural gradient tests (without boreholes) (Section 4.1.2)
4 - Natural gradient tests (multi-well) (Section 4.2.2)
5 - Drift and pump back (Section 4.2.1)
6 - Forced gradient (multi-well) (Section 4.2.2)

5.3. Quantity of tracer

The quantity of tracer which should be used for a tracer test depends on the following factors: the type of test being performed, the background concentration(s), what dilution is likely to occur between the injection and sampling points and the likely residence time for the tracer especially for tracers which may decay/degrade with time.

For single borehole dilution experiments, the recommended quantity of tracer required should be sufficient to raise the concentration in the borehole to between 100 and 1000 times the background concentration. This allows the progressive dilution to be monitored over a broad concentration range and, for most tracers, minimises the analytical costs. A wider concentration range may require sample dilution which adds costs and may introduce errors.

For point-to-point tracing the choice of tracer quantity is a critical factor in experiment design. Too little will result in concentrations below detection which could be wrongly interpreted as non-arrival. Too much tracer could result in a coloured surface water course, tainted public water supply and potential health problems. Deciding on the quantity of tracer is therefore possibly the highest risk decision to make in planning the tracer test.

A number of ways have been suggested, most of which are for homogeneous porous media. For fractured media, where flow may be through one or two major fractures, applying the homogeneous model approach can greatly overestimate the mass of tracer required.

The type of tracer test will also affect the mass required, for instance in radial converging flow it is likely that less tracer will be required than for a natural gradient test over a long distance where lateral dispersion will be greater. In addition to dilution caused by dispersion and diffusion, ion exchange and adsorption will decrease the concentration (or mass) of tracer which arrives at the sampling point. The optimum amount of tracer will result in a peak concentration which is 10 to 100 times the background concentration at the sampling point(s). This allows detailed definition of the breakthrough curve including time of first arrival and the peak.

Property	Tracer Type								
	Lycopodium	**Colloid**	**Phage**	**Inorganic salts**	**Fluorescent tracers**	**Fluoro-carbons**	**Organic anions**	**Radio-isotopes**	**'Natural'**
Conservative ?	N	N	N	N/C	N/C	N	C	C	N/C
Quantifiable ?	N (Yes if dyed)	Y	S	Y	Y	Y	Y	Y	Y
Sampling ?	P	S	S	I/S	I/S/P	S	S	I/S	I/S/P
Detectability	?	H	H	L	M	H	M	H	M
Toxicity -actual	O	O	O	O/C	O	O	O	C	O/C
Relative cost (tracer and analysis)	E	E	E	C	C	E	E	E	C
Ease of Use	D	D	E	E	E	D	E	D	E
Type of medium for which suitable	K	K/F/G	K/F/G	K/F/G	K/F/G	F/G	K/F/G	K/F/G	K/F/G
Types of test for which suitable*	3	1,6	4	1,2,5,6	1,2,3,4,5,6	6	1,2,4	1,2,5,6	3,4

Key.

Conservative ?	C - Conservative	Detectability	? - Uncertain
	N - Non-conservative		L - Low (x 10^5 dilution)
Quantifiable ?	N - No		H - High (x 10^{10} dilution)
	Y -Yes		M - Medium (x 10^8 dilution)
	S - Semi-quantifiable	Toxicity*	O - OK
Sampling ?	P - Passive detector		C - Possible concern
	S - Sample of water required	Relative cost	E - Expensive
	I - In situ measurement possible		C - Cheap
Ease of Use	D - Difficult	Type of medium	K - Karst
	E - Easy		F - Fractured
			G - Granular

* Types of test for which suitable - see Table 5.1 for key.

Table 5.3. **Summary of tracer types and important properties (adapted from Hobson, 1993)**

Box 5.1 Examples of tracer quantities (using one-dimensional Fickian dispersion)

1. Heath House (Triassic Sandstone) - Coleby et al 1996

Distance between injection and sampling point:	20 m
Depth of borehole(s)/injection pulse:	120 m
Dispersivity estimate:	2 m
kinematic porosity:	0.14
Well diameter:	0.25 m
estimated peak concentration:	100 µg/l
Calculated mass required*:	58.8 g
Calculated mass required[‡]:	4137.9 g
(Injected mass:	40.0 g)

Peak concentration (measured) after injecting 40 g:	1.8 µg/l
(Mass required to achieve 100 µg/l peak:	2222 g)

* using equation 5.1 only

[‡] using equation 5.1 and adjusting for radial flow

2. Banterwick Barn (Upper Chalk) - Ward et al, 1996

Distance between injection and sampling point:	70 m[1]	70 m[2]	284 m[1]
Depth of borehole(s)/injection pulse:	100 m	100 m	100 m
Dispersivity estimate:	7 m	7 m	28.4 m
kinematic porosity:	0.001	0.001	0.001
Well diameter:	0.2 m	0.2 m	0.2 m
estimated peak concentration:	100 µg/l	100 µg/l	100 µg/l
Calculated mass required*:	130 g	130 g	528 g
Calculated mass required[‡]:	286 g	286 g	4711 g
(Injected mass:	50 g	50 g	100 g)

Peak concentration (measured):	62 µg/l	37 µg/l	1.0 µg/l
(Mass required to achieve 100 µg/l peak:	81 g	135 g	10000 g)

* using equation 5.1 only

[‡] using equation 5.1 and adjusting for radial flow

[1] tracer injection prior to start of pumping

[2] tracer injection at steady-state

Perhaps the most useful method for providing an estimate of the quantity of tracer required is to use a simple formula based on one-dimensional Fickian dispersion. It uses estimates of dispersivity, α, the cross-sectional area of the injection pulse, A, distance between injection and sampling points, r and the maximum peak concentration, c_m to estimate the mass of tracer, M, required for injection;

$$M = c_m A\sqrt{4\pi r\alpha} \tag{5.1}$$

Where tracers which undergo decay (phages and radioisotopes) or sorb are used a correction should be considered for this when calculating the mass required.

The value for dispersivity can be approximated as one tenth of the scale of investigation, i.e. one tenth of the distance between injection and sampling points.

Equation 5.1 can be applied to natural gradient tests directly whereas in radially converging tests over relatively short distances, the effects of radial flow need to be considered. The mass calculated from equation 5.1 should be multiplied by a factor equal to the kinematic porosity, n_e multiplied by the circumference of the circle of radius, R equal to the distance between injection point and sampling well divided by the diameter, d of the injection well to determine the required mass of tracer, M_2;

$$M_2 = M \times \left(\frac{n_e 2\pi R}{d} \right) \tag{5.2}$$

More complicated methods are available for estimating the mass of tracer required. These require developing numerical models of the hydrogeological conditions prevalent and attempting to predict the necessary quantity of tracer. Aquifer parameters can be varied over likely ranges to predict the behaviour of the tracer for different scenarios (Barker, 1986).

Box 5.2 Monte Carlo approach for estimating tracer quantities (Barker, 1986)

A modelling approach was used to estimate the amount of dilution of a tracer/pollutant that would occur during groundwater transport through fissured Chalk between two points (injection and sampling) and hence determine a suitable quantity of tracer to use to ensure detection.

Because few of the relevant physical parameters which control movement of the tracer can be ascribed with any confidence, a probabilistic approach was used. A relatively simple model was adopted and a large number of simulations were performed using a wide range of randomly chosen (realistic) parameter values (the Monte Carlo technique) to yield distributions of results rather than a single value. The model considers mixing, dispersion and matrix diffusion, volume abstraction rate (at a pumping well), proportion of fissures contributing, head gradient and transmissivity. The model enabled probability values for the capture of different volumes of tracer by the abstraction well, estimates of dilution factors and travel times. For the situation being investigated, input tracer volumes of between 10-20 m^3 and transport over 3.2 km were used. It was found that the probability of capture of the tracer by the well abstracting at a rate of 2.3 x 10^4 m^3/day was greater than 75% with a travel time between 2-7 days. Dilution factors of between 5 x 10^4 (for non-diffusing tracers) and 1 x 10^{10} (for diffusing tracers) were expected.

Lenda and Zuber (1970) also present a graphical method for determination of the amount of tracer required for an experiment which are based on knowing (or estimating) porosity and dispersivity.

Experience has shown that even where due consideration has been given to the problem, the estimate of mass required can be inadequate, especially in fractured media. Previous experience of similar tracer tests in the same formation should therefore be considered and used in the selection process. Where uncertainty still remains, provision should be made for treating abstracted water should the need arise. This is discussed further in Chapter 6.

6. UNDERTAKING A TRACER TEST

After selection of the test method and the tracer for solving the problem being addressed, it is necessary to undertake further detailed planning for the practical aspects of the tracer test. These practical aspects should include examination of the boreholes, injection and sampling points, maintenance of equipment, selection of tracer injection and sampling methods, measurement of hydraulic parameters and other environmental parameters as well as identifying staffing needs. Of key importance is obtaining permission to undertake the test from the Environment Agency and other relevant bodies. The schematic diagram in Figure 6.1 provides a guide to assist with tracer test planning.

6.1. Reconnaissance

For a safe, efficient and trouble-free operation, preliminary practical planning is advisable. This planning should involve an inspection of the field area, borehole completions, pumps and discharge locations in order that appropriate remedial measures or maintenance can be undertaken before the start of the testing. The inspection should involve examining and testing the function of pumps, flowmeters and other monitoring equipment; ensuring safe access to sink holes, injection wells and springs etc.; ensuring discharge pipes and ditches are unobstructed; inspection of any other potential electrical, mechanical or physical element which is important for the smooth running of the tracer test. Details should be recorded to aid in the design of the tracer injection and sampling procedures.

The reconnaissance stage of the tracer test enables provisional protocols to be developed. For instance the best access routes, order of borehole/spring sampling, volumes of tracer required, size of borehole clamp, and identification of any specialist equipment that may be needed etc.

6.2. Environmental measurements

In addition to the measurements that will be required directly as a result of the tracer testing, consideration needs to be given to other environmental conditions and appropriate measurements made. Recording environmental parameters such as meteorological data, regional groundwater levels may be important for interpreting the results especially where the tracer test is prolonged and water levels are likely to change significantly. Seasonal changes or isolated events (e.g. heavy rainfall) may have a significant effect on the hydrogeological conditions and affect the test data. Knowledge of the prevailing conditions is also important in order that the test can be placed in context and compared with other tests if necessary. Sometimes, additional measurements may not be necessary because water level monitoring data may be available from the Environment Agency and meteorological data from the Meteorological Office. However the measurement frequency may not be sufficient and additional measurements may be needed.

In addition to these parameters, other potential sources of tracer in the aquifer should be investigated and, where necessary, a background sampling programme undertaken to examine any changes in background tracer concentration which may affect the test results.

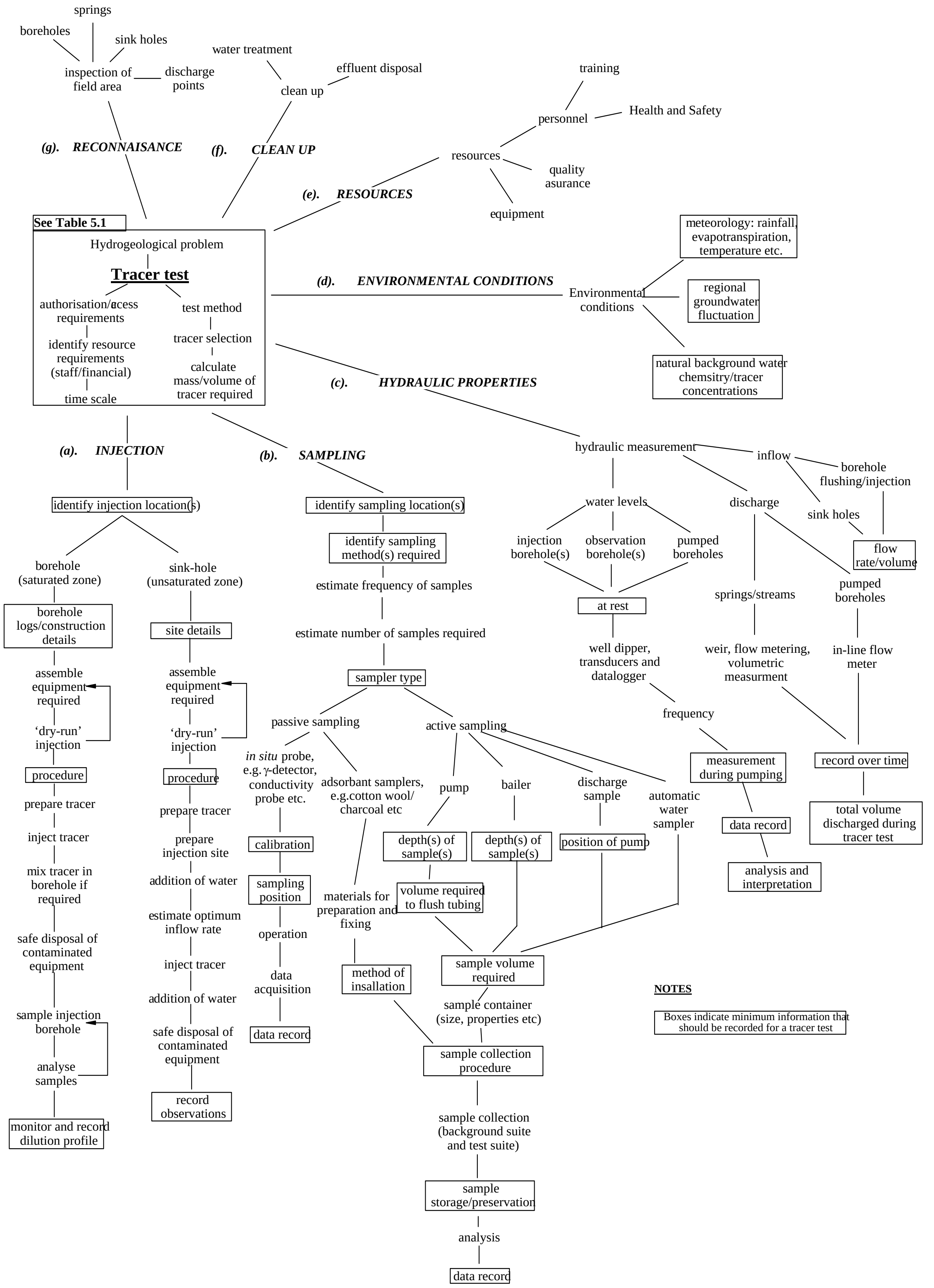


Figure 6.1. **Schematic overview of a tracer test as a planning guide**.

6.3. Tracer injection

Injection of tracer can theoretically take place at any location where the tracer will or is likely to enter the groundwater system, for example boreholes, sinking streams, soakaways and a quarry floor. In general, injection points fall into one of two categories: direct and indirect. Direct injection is where the tracer is placed into the groundwater directly, for example by borehole injection, and indirect injection is where there is a component of transport through the unsaturated zone before reaching the saturated zone, for example via a soakaway.

Tracers may be introduced as a pulse, over a short period, or as a continuous source. This will depend on the objectives of the study, the methods available for analysis of data and the mass of tracer to be injected.

6.3.1 *Direct injection*

In major aquifers, direct injection of tracer is usually into a borehole or boreholes penetrating the saturated part of the aquifer. This injection can be into the full thickness of the aquifer or in to just part of it, for example by using inflatable packers to isolate a section of borehole or into a partially penetrating piezometer.

In its simplest form the injection could be by pouring a volume of tracer into the top of the borehole. This is generally unsatisfactory because the tracer at best only enters the uppermost part of the aquifer and at worst remains static in the casing. It is therefore advisable to plan a well controlled injection.

If an injection into the whole thickness of the aquifer is required, the borehole must penetrate the full thickness. The reconnaissance stage of the fieldwork and the preliminary work should have provided the completion details of the borehole, the position(s) of screen and casing. Cased parts of the borehole are potentially static flow regions and so tracer injected into this part of the borehole may remain there and play no part in the tracer test, lead to a poorly defined injection pulse or interfere with operations as sampling equipment is lowered through this section of the borehole.

There are a number of ways to achieve uniform tracer injection, each varying in complexity. The simplest way is to introduce the tracer into the screened or open section of the borehole via a weighted hose. Experience has shown this method to have worked well in boreholes up to 100 m deep. A more detailed description of this type of injection, including the procedure and precautions, is provided in Appendix A.

Before and after injection, tracer concentrations should be monitored to determine background concentrations and subsequent initial tracer concentration and dilution. These data are important because they allow accurate definition of the shape of the injection pulse which will be required for analysis of tracer breakthrough curves.

A borehole injection of this type is often described as an instantaneous injection. In reality it is an instantaneous injection with an approximately exponential decay. The decay is determined by the flow geometry through the borehole. The decay data may be used for single borehole dilution if the test is a natural gradient test and provide information on major inflow/outflow zones.

Variations on this injection method include incorporating a circulating pump within the injection borehole to ensure good mixing and avoidance of density effects etc. The disadvantage of the circulating pump is that it removes the ability to determine significant flow horizons.

A circulating pump is also recommended if a continuous injection of tracer is to be performed, in order to maintain a uniform concentration profile within the borehole during the injection period. It should be noted that injection of water/tracer into boreholes will result in a head change and the effects of this on the flow field should be considered.

In the case of only a few known flow horizons within the borehole, it may be more appropriate to consider the use of packers to isolate these zones, thereby reducing the borehole volume and allowing a more efficient injection. Also, different tracers can be injected into different zones, Figure 6.2. Injection within the packered zone can be achieved by pumping a tracer into the zone from the surface or by direct release of the tracer in the zone. A simpler method is to use a hose which is lowered down the borehole until the bottom is adjacent to the flow zone. Sufficient tracer is then poured down the hose until it flows out of the lower and, hopefully, into the flow zone. Water can be added after the tracer to flush out the hose.

Other alternative methods and variants on the above are available and often reported in the literature, for example Sen et al, 1989. In this case, for a tracer test in a shallow confined sand aquifer, a special tracer injection chamber was manufactured which allowed uniform mixing of the tracer before its release.

6.3.2. *Indirect injection*

When release of tracer is not directly into the saturated part of the aquifer the injection is referred to as indirect. This type of injection may be chosen by design or by necessity. In general less control can be achieved by indirect methods.

For shallow boreholes which are located in the unsaturated zone, sink holes and soakaways which do not have inflows, some flushing may be required to force the injected tracer in to the hydraulically active parts of the aquifer. It is preferential to start a flow of water into the injection point before injecting the tracer. This will act as pre-conditioner and enable a suitable injection rate to be calculated. After injection of the tracer, a further period of water injection should follow to assist with transmission of the tracer. It is preferential not to flood the borehole with water at a high inflow rate because the result may be to spread the tracer laterally within the unsaturated zone. Better is a ‘trickle recharge’ so that a narrower wetted zone is established through which the tracer moves more rapidly to the water table.

If an injection point consists of a large diameter hole, it is worth considering allowing the tracer to soak through the base of the hole before starting ‘trickle recharge’ in order that as little dilution of the tracer as possible occurs in the hole.

Where surface features are active, the tracer can be added directly to the flow of water entering the injection point. Where a proportion of the flow does not enter the sink, e.g. in the bed of a river, either estimates of the amount of tracer which misses the sink need to be made or an injection method developed to maximise the amount of tracer which enters the sink. This could be the installation of a shallow borehole/pipe over the sinking point in the stream bed which will enable direct injection of tracer.

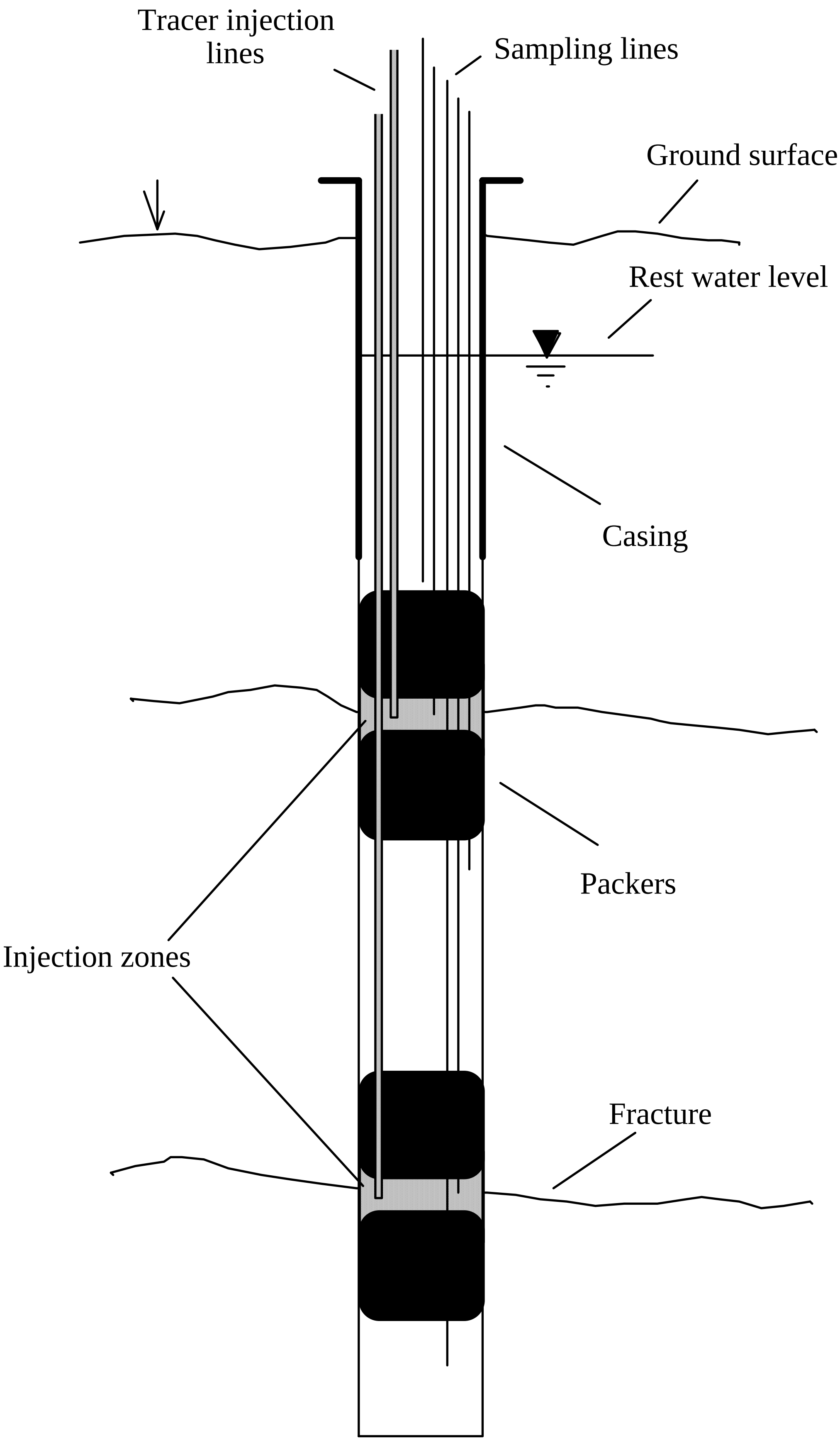


Figure 6.2. Schematic diagram showing isolation of fractures for direct tracer injection and sampling.

6.4. Sampling and tracer detection

When undertaking a tracer test it is necessary to carefully decide the locations which should be sampled. For natural gradient tests these points are generally springs, surface water courses and boreholes penetrating the aquifer as well as the injection point. The preliminary desk study coupled with the reconnaissance survey should have identified all possible discharge and sampling points. For large scale tests the ‘walk-over’ reconnaissance survey is extremely important for this purpose and also for identifying any unexpected needs. Subsequent preliminary testing may also indicate which of the sampling/injection points are most important in terms of the tracer test.

For forced gradient tests, the direction of groundwater flow is well defined. However heterogeneity may result in local variations and so it is prudent to consider additional sampling points as well as the obvious ones.

Collection of samples can be a very time consuming and expensive but is an essential part of the experiment. Thought should be given to alternative methods which reduce costs, e.g. automated samplers and/or passive detectors, although these may degrade the quality of the data by averaging over time or limiting the number and frequency of samples

Samples for background concentration measurement should be taken prior to the tracer injection and preferably over a period of time. Ideally, this period should be at least be equal to the expected duration of the tracer test. This allows a base line for detection to be determined and can be useful as a tool in tracer selection. For example, optical brighteners may not be suitable for tracing a sinking stream which is downstream of a sewage discharge point. Optical brighteners are commonly used in detergents and are therefore commonly found in waste waters.

6.4.1. *Injection point sampling*

Depending on the nature of the tracer test and injection point, it may be possible and necessary to sample the injection point to monitor the disappearance or dilution of the tracer. The results can be used to check that the tracer has migrated from the injection point and in defining the injection pulse shape, which may be needed for modelling of the breakthrough curve.

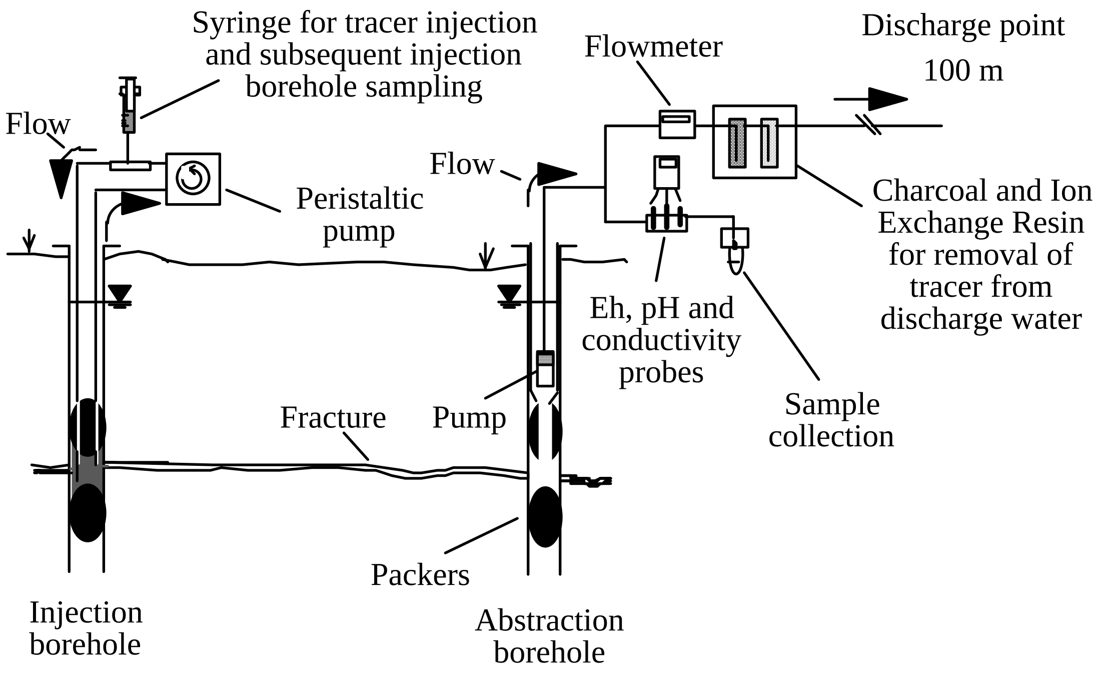
For borehole injection, it is possible to use a depth sampler or monitoring probe depending on the tracer and injection mode. Alternatively small volumes may be sampled from the re-circulation line or by pumping to the surface. It is essential that the procedure used causes minimal disturbance to the prevailing hydraulic conditions.

Because of the high concentrations of tracer relative to those which will commonly be encountered at the discharge or other sampling points, it is important to ensure that no cross-contamination takes place.

6.4.2. *Observation borehole sampling*

Depth samples or discrete measurements can be taken using a borehole sampler, e.g. bailer, shut-in-valve sampler, logging conductivity probe or ion-specific electrode depending on the type of tracer being used. Analysis of samples and their results will enable a depth profile to be obtained and measurements over time will enable a breakthrough curve to be constructed. A borehole pump will only provide an integrated sample.

Box 6.1 Example of tracer injection and sampling configurations for small scale test (Lloyd et al, 1996).



Alternatively, passive detectors could be used. These are detectors which are constructed of a material to which the tracer may adsorb, e.g. fluorescent dyes and organics to charcoal and optical brighteners to cotton (Smart, 1976). They can be assembled and any number lowered in to the borehole to be positioned at pre-determined depths, e.g. adjacent to a fracture.

Where an array of boreholes are to be installed for tracer testing, installation of dedicated multi-level samplers may be considered. These are designed to allow collection of discrete samples from different depths and minimise the borehole volume from which the samples are taken to reduce mixing and long residence times. For shallow applications, the multi-level samplers can be driven directly into the ground so that the samples are taken directly from the formation (Wealthall et al, 1988). Multi-level samplers can also be installed in existing boreholes using a series of packers to isolate the zones, e.g. Westbay packers.

The samples are taken by use of a small integrated sampling pump or by applying a suction at the surface. A sample manifold board allows near simultaneous sampling of all horizons (Hitchman, 1988).

6.4.3. *Sampling discharging springs, seepages and pumped or artesian wells*

Sampling points which discharge water naturally are relatively easy to sample. The discharging water may be sampled by hand, by automatic water sampler, it may be diverted through flow-through cells for real time analysis or the probes placed directly in the water flow. Passive detectors and filters could also be used by placing them within the flow of water depending on the type of tracer being used.

are exposed to surface influences e.g. sunlight, rain, wind, vandalism etc., it may be necessary to shield the samplers.

In addition to sampling for tracers, a measure (or estimate) of discharge should be made to allow calculation of mass recovery.

6.4.4. Sample and tracer handling

Perhaps the most important point to make is that extreme care must be taken when handling samples and tracer because of the potential for contamination. The injected tracer has, not untypically, a concentration which is 10^7 times greater than the minimum detectable limit. It is therefore easy to see how significant contamination can occur.

It is essential therefore that personnel are thoroughly trained and briefed on the sample collection procedures. Ideally, the persons injecting the tracer should not take part in the sampling to avoid contamination. This however is not always possible and so appropriate disposable protective clothing should be used. Table 6.1 lists a series of simple precautions which should be observed when handling tracers and samples.

Table 6.1. Precautions which should be taken when handling tracer test samples.

1. Concentrated dyes should not be handled or stored in the same rooms as those used for sample storage or analysis.
2. Personnel who prepare and inject tracers should ideally play no part in sampling (including background) or analysis, and vice versa.
3. Never take tracers which have not been prepared into the field. Always prepare tracers as solutions or in an appropriate form before going into the field.
4. When transporting tracers, ensure that all apparatus is protected form potential contamination. Make sure concentrated tracers are sealed in rugged leak-tight, unbreakable, double thickness/layer containers in the event of an accident. Ideally, concentrated tracer and sampling equipment should not be transported in the same vehicle.
5. Keep track of clothing worn by injection personnel. Make sure it does not return on site during the test, and be sure that it is not worn by sampling personnel. (Ideally use disposable protective clothing)
6. Be prepared to invest in new apparatus for an important test (e.g. new lycopodium spore nets, new sample bottles, new hoses for samplers etc.).
7. When handling tracer solutions in the field, always wear disposable gloves and coveralls against spillage (for some tracers protective clothing and apparatus may be essential). Always handle tracers with caution and arrange injection conditions to eliminate spillage or unwanted spreading of tracer. Test injection procedures beforehand, using water in a “dummy run” to identify any problems.
8. Prepare a plan of action for implementation in the event of a spillage. In the case of radiotracers, appropriate decontamination measures will be required and provision made for isolating and cleaning up contaminated areas.

Once the samples have been collected, they should be preserved as appropriate and transported to the location of analysis as rapidly as possible. If analysis cannot take place immediately, samples must be stored to avoid degradation. Care needs to be taken in selecting sample containers, they must be leak proof, non-breakable, non-sorbing and non-reactive. The environmental conditions for storage must also be considered and optimised. For example, where fluorescent dyes or optical brighteners have been used, samples must be stored in the dark, where bacteriophage have been used samples must not be frozen and where radioactive samples are stored, adequate shielding must be available to protect personnel. The collection and storage of several radioactive samples in one place could result in a concentration of activity and hence a significant radiological hazard. This risk must be assessed and appropriate precautions, e.g. shielding, taken before the test begins.

6.4.5. *Sampling frequency*

The frequency of sampling depends on the nature of the tracer test. Where a simple test to prove a connection is being employed, the sampling frequency is of less importance than if a travel time is to be determined or a detailed breakthrough curve is required. In the former case, passive samplers can be employed which can be removed and replaced at a pre-determined frequency. For quantitative studies, the frequency of sampling must be clearly defined. Approximations of travel time may be possible if there is sufficient knowledge of aquifer properties and sampling frequency can be based on this. Where there is insufficient knowledge of aquifer properties, then the experimenter must err on the side of caution and take more samples than may be really necessary. Selective analysis of these samples will allow costs to be kept to a minimum.

In general, where a breakthrough curve is to be defined, it is useful bear in mind that the time between first arrival of tracer and the peak concentration is much shorter than the time between the peak and the last arrival of tracer. More frequent sampling is therefore required during the earlier stages of the experiment.

6.5. Disposal and treatment of effluent/clean up

A tracer test should always be designed so that the concentration of tracer expected at the sampling point will not pose a potential environmental contamination problem. Also, calculations of tracer mass/volume should have been performed to estimate the maximum concentrations down gradient. However, because of the uncertainty of tracer testing and the behaviour of tracers in the sub-surface it may not always be possible to be certain. In which case, it may be appropriate to consider treatment of the discharging water stream if it is possible (however unlikely) that the presence of tracer in the effluent water could pose a problem, e.g. tainted drinking water and coloured surface waters. The treatment will depend on the tracer being used but could range from total removal of waters by tanker for industrial treatment/landfilling to chlorination for removal of bacteriophage, charcoal filtration and/or uv treatment for fluorescent dyes or ion exchange columns for organic and inorganic ion tracers.

6.6. Troubleshooting

Because of the experimental and practical nature of tracer testing, problems can frequently occur. Problems relating to equipment operation should be minimised by following the preparation procedures recommended. The most common problems are pump failure and automatic water sampler failure. The failure of a pump and the effect this has on the hydraulic gradient can negate the test results if rapid action is not possible. Repairs or a replacement should be effected immediately and the tracer recovered and disposed of even if the test is to be aborted. This will ensure that the tracer does not contaminate the aquifer and may allow repeat testing using the same tracer. Failure of the water sampling equipment should be rectified as rapidly as possible. A spare sampler, fully charged batteries and replacement bottles should always be available to replace any problem or broken component.

Box 6.2 Examples of sampling frequency (h:mm)

Radially converging test (Triassic sandstone), (Coleby, 1996)

distance from injection to sampling point: 20 m

t = -1:00 (pre-injection) to 0:00	every 5 minutes
t = 0:00 to 1:15	every 5 minutes
t = 1:15 to 13:50	every 15 minutes
t = 13:50 to 21:50	every 20 minutes
t = 21:50 to 53:10	every 50 minutes
t = 53:10 to 121:50	every 1 hour 25 minutes
t = 121:50 to 192:50	every 1 hour 30 minutes
t = 192:50 to 287:50	every 2 hours

Radially converging test (Chalk), (Ward, 1996)

distance from injection to sampling points: 70 m and 284 m

t = -1:00 (pre-injection) to 0:00	every 15 minutes
t = 0:00 to 2:25	every 15 minutes
t = 2:25 to 6:50	every 30 minutes
t = 6:50 to 23:50	every 1 hour
t = 23:50 to 190:00	every 2 hours

Large scale natural/prevailing gradient test (Ward, 1997)

distance from injection well to sampling points: up to 4000 m

t = - 24 hours to 0:00	full background suite
t = 0:00 to 5 days	every 15 minutes (composite of 4 samples every 1 hour)
t = 5 days to 13 days	every 30 minutes (composite of 4 samples every 2 hours)
t = 13 days to 37 days	every 60 minutes (composite of 4 samples every 4 hours)
t = 37 days to 90 days	every 120 minutes (composite of 4 samples every 8 hours)

Non-recovery of tracer is major problem. It can result in a lot of uncertainty and can be due to either practical or physical problems. If after a reasonable period of time, no tracer has been detected a review should be undertaken before making any decision. The experimental conditions should be checked to ensure that the sampling equipment is operating correctly, the samples are not being adversely affected and the analysis method is correct. The injection point should also be checked to see if the tracer has disappeared. Where possible injection borehole dilution should be monitored routinely or tracer flushed into the aquifer. In addition to examining the practical aspects of the test, a review should be made of any physical conditions (hydrogeological or environmental) that may be adversely affecting the test. For example, are there any other possible discharge points, has any other pumping started nearby, has the natural gradient been overcome or has it changed since the preliminary planning stage? If none of these provides the answer then the results may indicate that there is no hydraulic connection or the tracer has been over-diluted. The practical solution, if resources allow, is to continue sampling but at a reduced frequency or with passive samplers (if appropriate) and consider injecting a second, different tracer at a higher concentration than the first.

If after sufficient time has elapsed tracer is still in the injection borehole, the hydrogeological conditions locally have changed or are poorly understood. The tracer should therefore be removed from the borehole and disposed of appropriately. If tracer is not removed it may cause inadvertent contamination of other boreholes by the tracer being transferred on well dippers, water samplers etc.

6.7. Data and data analysis

6.7.1. *Data recording*

It is important that when undertaking a tracer test, considerable time is devoted to recording data which may prove essential at the evaluation and interpretation stage. Experimenters should be encouraged to record details of all equipment and facilities used, their operation, any problems encountered and any unexpected events as well as recording details of conditions during the periods of smooth operation. It is recommended that field data are recorded on pre-prepared data sheets, where possible, with the provision for recording a brief summary of experimental conditions. For example, the borehole location, identifier, NGR, tracer test title, status of the information and experimenter's name etc.

The following additional information should be recorded where appropriate:

- Geographical location of test site, boreholes, springs etc. (including NGR altitude etc.). Ideally a map should be prepared showing all the relevant features.
- Geology of study area at the relevant scale (using Solid and Drift maps and borehole records).
- Meteorology (meteorological data for the area over the period of the experiment). This can be obtained from the Met. Office or by using a portable met. station.
- Background concentrations of likely or selected tracers. More than one suite of samples should be taken to determine spatial and temporal variation.
- Background chemistry of groundwaters. This could affect the behaviour and detectability of tracers.
- Rest water levels, regional hydraulic gradient and temporal changes in water level/gradient.
- Pump details settings etc.
- Pump discharges and spring discharges. Important for quantitative interpretation of results
- Drawdowns in injection well, abstraction well and other observation boreholes. Allows calculation of local hydrogeological properties.
- Effects on springs etc. from pumping. Important for understanding effects of pumping on groundwater flow.
- Local hydraulic properties (transmissivity, hydraulic conductivity, storage).
- Tracer test method selected.
- Tracers chosen (details of suppliers and preparation).
- Mass of tracer selected and injected.
- Volume of tracer injected
- Method of injection and procedure.
- Time and date of injection.
- Location and details of samples/samplers (time, depth, location, number, sampler volume).
- Time of sample collection.
- Temperature (of sample/groundwater).
- Sample storage details and conditions.
- Time and date of analysis.
- Location of analysis
- Procedure and method for analysis and details of any preparation required.
- Results of analysis
- Standards/calibration etc.

6.7.2. *Database requirement design and presentation*

The data obtained during the tracer test should be clearly presented regardless of the outcome. Details of a tracer test in which there was no recovery of tracer should be also archived in exactly the same manner as if there had been for recovery.

The database of results should include a detailed index of all parameters measured and observations made as well as any additional information which may be important during the later stages of the test evaluation.

Where tracer concentrations are recorded, they should be presented in original format and in corrected format (where applicable), i.e. taking into account background concentrations and radioactive decay etc.

A data report should be prepared which summarises all relevant information and identifies the location of original data. Breakthrough curves should be plotted as concentration against time and concentration against volume discharged. Dilution profiles should be plotted as concentration measurements against depth for each sampling episode on the same plot. For these dilution profiles with time, a semi-logarithmic plot is recommended. A suggested structure for a data report is shown in Table 6.2 and an example is provided in Appendix C.

Table 6.2. Suggested structure for tracer test data report

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1. Title page.
2. Summary sheet (see Section 10 for recommended format)
3. Index
4. Project staff list and contact addresses etc.
5. Site details
    - geography,
    - geology
    - hydrogeological
    - geochemical
6. Tracer test
    - injection
    - sampling
    - other measurement
    - analysis
7. Data
    - complete listings or detailed summary with clear instructions on locating original data.
8. Results
    - processed data and breakthrough curves, dilution profiles, etc.

6.8. Field Equipment

This section provides a list of the basic equipment which will be required to undertake the two types of tracer test which are most commonly employed. It cannot cater for all eventualities but provides a starting point. Even tests of the same type may be slightly different and so needs may vary. Where more complex testing is being considered, specialist equipment will also be necessary.

Table 6.3 Equipment needed for single borehole dilution test

- Well dipper
- Tape measure (>30 m)
- Injection hose (min diameter 10 mm)
- Hose couplings (jubilee clips and inserts)
- Weight (for attaching to end of hose)
- Hose/borehole clamp
- Funnel(s)
- Tracer
- Volumetric containers
- Water
- Sampling device
  - depth sampler
  - down hole logging probe, e.g. conductivity/temperature probe
- Sample containers
- Sample storage facility, e.g. cool box
- Analytical equipment, e.g. fluorimeter, conductivity probe, ion selective electrode
- Trained staff
- Data sheets
- Tools
- Protective clothing and accessories
- Waste/contaminated equipment storage facility

Optional extras (for more complex testing)

- Borehole Packers
- Inflation lines
- Gas supply (for packer inflation)
- Tripod
- Winch and cable/rope

Table 6.4 Additional equipment needed for radially converging tests

Equipment as Table 6.3 plus

- Pump and accessories, rising main and discharge pipe
- Generator/power supply
- Flow meter(s)
- Water level recorders or pressure transducers and data acquisition system (logger, PC etc.)
- Data record sheets for water level measurements, discharge measurement, sample records etc.
- Automatic water sampler(s) and accessories
- Suitable discharge location/facility (far enough away to avoid the possibility of re-circulation of tracer or introduction of hydraulic effects)
- Discharge water treatment

6.9. Costs

A precise estimate of the costs of a tracer test cannot be made due to a wide range of variables including the hydrogeological setting, existing setup duration of test etc. However previous experience provides a guide given in Tables 6.5 and 6.6.

Table 6.5 Minimum staff requirements for tracer testing

1. *Single borehole dilution testing (Chalk and Sandstone)*

Preparation (planning etc) -	1 person-day
Preparation (equipment) -	1 person-day
Injection (100 m borehole) -	2 person-days (2 people)
Sampling -	3-5 person-days
Analysis (if laboratory required) -	1 person-day
Report -	1 person-day

2. *Radial converging tracer test*

Example for Chalk over radial distances < 300 m and Sandstone < 50 m.

Preparation (planning etc) -	2 person-days
Preparation (equipment) -	2 person-days
Injection (100 m borehole) -	2 person-days (2 people)
Sampling -	5 - 14 person-days (1-2 people)
Analysis (if laboratory required) -	2 person-days
Report -	2 person-days

3. *Large scale natural gradient test*

Example for Chalk over distances < 4000 m

Preparation (planning etc) -	3-5 person-days
Preparation (equipment) -	2 person-days
Injection (2-3 points) -	2 person-days (2 people)
Sampling* (2 - 3 points for 50 days)	10 person-days (1-2 people)
Analysis (if laboratory required) -	3 person-days
Report -	3 person-days

* assumes automatic water sampler(s) used

Table 6.6 Costs of tracer (1997 prices)

Fluorescein = £25 for 500 g of powder (Aldrich/Fisher etc.)
= £200 for 25 kg of powder (Holliday dyes and chemicals, Leeds)

Rhodamine WT = £348 for 10 kg (20% soln.) (Holliday dyes and chemicals, Leeds)
Rhodamine WTS = £20 per pint or £92 per gallon (US) from Cole Palmer

Amino G Acid = £15 for 100 g (Aldrich/Fisher etc.)

Bacteriophage = £300 for 1 litre of 10^{12} pfu/ml (Alcontrol UK)

Sodium chloride (NaCl) = £5 for 10 kg (Widely available)

Potassium Bromide (KBr)= £20 for 1 kg (Aldrich/Fisher etc.)

Lithium Bromide (LiBr) = £55 for 1 kg (Aldrich/Fisher etc.)

PFBA (organic anions) = £10 - £20 per 10 g (Aldrich/Fisher etc.)

Tritium = £150 for $1.11\text{x}10^8$ - $1.85\text{x}10^8$ Bq (Amersham)
^{131}I = £150 for $7.4\text{x}10^7$ Bq (Amersham)
^{125}I = £200 for $1.8\text{x}10^7$ Bq (Amersham)

7 DATA ANALYSIS

7.1 Introduction

This chapter provides a guide to the principles and practice of analysing tracer tests. Before a tracer test is conducted, the likely method of analysis (if any) should be decided and the test conducted in such a way that the analysis is feasible. For example, almost all methods of analysing tracer tests assume the groundwater velocity to be steady so transient conditions, as pertain immediately after a pump is turned on, need to be avoided. In some cases a consideration of the difficulties of data analysis may suggest that a tracer test is not a worthwhile exercise.

The view is taken in this report that it is not appropriate to prescribe methods of data analysis except in the simplest cases. It is strongly recommended that data analysis to reveal aquifer transport parameters should be carried out by someone with a background in groundwater modelling. Such a person will be able to make a judgement as to the applicability of a given method of analysis in relation to: the quality of data obtained, the quantity of data (including the percentage recovery), and the ultimate use of the parameters obtained. Normally parameters from tracer tests are used in predictive groundwater models and a groundwater modeller will be able to assess whether the parameters obtained will be compatible with the model in which they are to be used. It is clear, therefore, that it is advisable to involve a modeller at the planning stage of a tracer test. If that is not possible, the test should be performed under very tightly controlled and monitored conditions to ensure that the data ultimately lend themselves to analysis.

This chapter takes non-mathematical view of possible approaches to analysis and is intended to be of general interest. Details of models and software are given in Appendix B which is intended to aid those who actually perform the data analysis. This chapter and Appendix B aim to: (a) to explain general principles, (b) introduce the standard approaches, (c) provide a guide to software, and (d) provide adequate references to publications that can be consulted for details.

It must be recognised that tracer test interpretation can be performed in a variety of ways depending primarily on the purpose of the tracer test. These approaches are summarised in Table 7.1 and are elaborated upon in this chapter and, in a more mathematical manner, in Appendix B. The levels of analysis suggested in the table are not completely distinct and significant overlap exists between neighbouring levels.

In general it is hard to avoid the use of a model in analysing a tracer test so the next section deals with model application. However the model need not be process-based. Most of the general statements in this section relates both to environmental tracer ‘tests’ and artificial tracer tests although the latter topic is of central importance here. It will be assumed that the tracer is either in solute or particulate form. Heat can be used as a tracer and is subject to analogous processes (e.g. diffusion) as solutes, but heat will not be treated explicitly.

7.2 Models in tracer testing

The need to use models and the type of model employed in analysing tracer tests is obviously related to the purpose of the test being undertaken. If the purpose of the test is simply to establish connection between two points, no conceptual or mathematical model is required. If the purpose is both to establish connection and to indicate travel times then there will at least be an implicit model in terms of assumptions about the rate of tracer movement relative to the water.

Table 7.1 Hierarchy of tracer-test analysis

LEVEL	TYPE	RECORD	SEE
1	Connectivity	Yes / Inconclusive	
2	Travel time	Time of: first arrival, maximum concentration, etc.	
3	Statistical	Statistics (mean, s.d. etc. of travel time) or, equivalently, moments of concentration	Section D5 Eqs. (D1)-(D4)
4	Transfer function	Coefficients of transfer model	Section D5 Table D1
5	Analytical solutions of transport equations	Physical parameters of the model (few)	
6	Numerical modelling	Physical parameters of the model (few - many)	Section D12
7	Constrain prediction models	Raw data	

Consider such a test which is allowed to continue until a peak of tracer is observed, and then the test is stopped and the distribution of travel times computed from that peak. In this approach there is an implicit assumption that there is a single pathway through the system; it might, however, occur that a further peak carrying a far greater amount of tracer would have followed. The point being made is that the analyst does well to consider the form of model, conceptual if not mathematical, being used, implicitly if not explicitly.

Normally the aim of a test is to derive transport parameters characterising the system. Normally, but not always, the derived parameters will be intrinsic properties of the rock, at some scale. More precisely they will be the parameters in the mathematical model being employed. However, the ultimate objective cannot be one of collecting model parameter estimates, the purpose will almost always be to predict the movement of the water, chemicals, particles etc. through the system. The purpose of the model in this case is essentially to extrapolate from the tracer test to the real-world situation of interest. For example, the tracer test might involve several tracers with different sorption characteristics; given adequate laboratory information on the sorption characteristic of these tracers on the rock type and also of a pollutant of interest, extrapolation should be possible.

It is this ability to extrapolate that imparts a strong preference of process-based models over ‘system theory’ models. A system based model can provide little if any guidance on what might happen outside the conditions the pertained during the tracer test being analysed; the parameters of such a model will be specific to the test conditions.

Sometimes tracer testing is carried out as part one element of an investigation, for example, along with a pumping test or a clean-up exercise. In these cases the tracer test results will constrain the interpretation of the behaviour of a system. In the pumping test case, for example, a tracer might be used to establish whether or not leakage was occurring within the time-scale of the test between a pumped aquifer and an adjacent aquifer. In such cases the ultimate aim of the interpretation model may be to improve the conceptualisation and parameterization of a groundwater system, possibly with flow of water being of more importance than transport within that flow.

A particularly important role for models is in simulating tracer test behaviour in order to help design the test. Decisions to be made are: what quantity of tracer to apply, where to monitor (if boreholes are to be installed), when to monitor, for what period and for how long. The difficulty is that in order to simulate a test accurately the results that the test is intended to give - the transport properties of the system - are required *a priori*. There is no easy way out of this problem: use must be made of information from previous tests in similar circumstances and, given that information, scoping studies using models performed.

7.2.1 *Process models and software*

The modelling of tracer tests is dependent on the same conceptual models of flow and transport that are used in other areas of hydrogeology. The literature on that topic is very large and it is not possible to provide a useful review in this report. The topic is reviewed in a set of reports produced for the NRA by BGS (Barker and Kinniburgh 1995).

The differences between tracer testing and more general transport problems include:-

- The tracers will be chosen such that their behaviour in the system under study is understood apart from those parameters of the system that the test is designed to determine. Mathematical models and software tools exist or can be developed.

- The tracer will be applied and detected in a controlled manner.

- The flow will often be controlled. This simplifies the geometry and boundary conditions of the system.

7.2.2 *Analysis without process models*

One modelling approach that is applied to tracer tests but is infrequently used in other branches of hydrogeology is the transfer-function method, which is outlined in Appendix B.

In principle, a simple tracer breakthrough curve can be characterised by statistics, such as the mean transit time or the transit time variance. An equivalent method is to use ‘moments’ (over time). These statistics correspond to parameters in a chosen ‘transit time’ (or ‘transfer’ function) model. Some transfer function models correspond to process-based models and therefore the same parameters are related to the physical and chemical parameters in those models.

If high quality data are obtained and tracer recovery is close to 100%, parameter calculations can probably be based on moment calculations. When, as is more common, tracer recovery is significantly less than 100% either a transfer function or a process-based model can be fitted to the data to obtain parameters.

Two more obvious weaknesses of the transfer function approach are that it cannot easily deal with transient flow conditions or conditions of heterogeneity (apart from by putting transfer functions in series).

7.3 Scale dependence in tracer testing

A problem that is revealed by tracer tests and which is an intrinsic problem in their interpretation is that of the dependence of parameters on scale. Specifically, tests over larger distances give larger dispersion coefficients or, equivalently, dispersivities. (The dispersivity is essentially the ratio of the spatial spread of a tracer divided by the distance travelled.) This is a reflection of the heterogeneous nature of the rock which causes increasing relative variation in transit time as travel distance increases. In granular systems this growth of dispersion with scale is far less pronounced than in fractured systems. The major aquifers of the UK are all fractured to some degree, so scale dependence of dispersion is a problem that must be faced.

The most serious result is that some parameters derived from tests at one scale cannot be applied with confidence to models at a larger scale. This is a large topic currently attracting a large amount of experimental and theoretical effort throughout the world.

7.4 Problem of uniqueness

There is always a uniqueness problem with tracer test interpretation unless a single peak is obtained (perhaps the observation of a single particle). The fact that this is generally so can be seen from the fact that each concentration measurement can be ascribed to a separate flow path through the system, that is a channel model with as many channels as observations. Clearly such a system is unlikely to even begin to represent reality except in some fractured rocks.

This problem is often encountered; for example, Moreno et al. (1983) fitted four models with near-equal success to a field tracer experiment in fractured rock. The models were: 2-paths with advection and dispersion (6 parameters); 3-paths with advection and dispersion (9 parameters); 1-path with advection, dispersion and matrix diffusion (4 parameters); and a channel model with advection and matrix diffusion (4 parameters).

Uniqueness problems reduce as the number of tracers used simultaneously increases and as the number of observation points along the tracer flow path are increased. Uniqueness is one element of the problems of model calibration and validation; a general discussion is given by Maloszeweski and Zuber (1993).

7.5 Fractured porous rocks

Some special considerations are needed in relation to tracer testing in fractured porous rocks such as the Chalk. When the flow in the matrix pores is negligible, such systems are referred to as 'double-porosity'. Adopting a relatively simple model of such systems, Appendix B (Section B.11) provides a mathematical approach to understanding tracer tests in such systems. Here a more qualitative view of the same problem is presented. The aim is to warn of potential problems in the analysis of tracer tests in double-porosity systems.

The essential behaviour of a double-porosity system to tracer injection is that the tracer moves with the water through the fractures but at the same time diffuses into the relatively immobile water in the matrix pores. Diffusion is a relatively slow process and diffusion over a distance of the order of one centimetre is about two days and over ten centimetres is about 6 months. Such time scales are important in determining how well a tracer test can be diagnostic of the aquifer transport parameters. We consider four regimes of behaviour as summarised in Figure 7.1.

Regime A: Suppose the tracer moves through the fracture systems from the injection point to the observation point in just a few minutes. Diffusion into the matrix will be negligible (unless the fracture apertures are less than about 0.1 mm) so the tracer test will reveal nothing about the nature of the matrix. The parameter that will be revealed will be the (kinematic) porosity of the fractures. (See Figure 7.1A)

Regime B: Now suppose the tracer moves through the system in a few hours. That will give the tracer time to diffuse a couple of millimetres into the matrix which is a significant distance in relation to the fracture apertures and therefore significant dilution will occur by matrix diffusion. Therefore the tracer test will reveal behaviour characterised by not only by the fracture porosity but also by the area for diffusive exchange and by the time for diffusion into a volume equal to the fracture volume. (See Figure 7.1B).

Regime C: When the tracer test is much slower, several months perhaps, it is likely that the distance that the tracer can diffuse into the matrix blocks will be of the order of the size of the blocks. The test will then be characterised by the time for diffusion through a block and the relative amounts of water in the blocks and fractures. (See Figure 7.1C).

Regime D: With very slow tracer tests (in relation to the time for diffusion through matrix blocks) the tracer concentration in the fractures and in the matrix will locally be similar. The tracer test will reveal nothing about the fracture or block sizes and the only parameter revealed will be the total porosity. (See Figure 7.1D).

Regimes C and D are more likely to relate to ‘accidental’ tracer tests where, for example, there is an accidental spillage or the deliberate application of a chemical such as a pesticide.

Having recognised that tracer tests carried out over different time scales reveal different parameters of a double-porosity system, it is obvious that a given tracer test is quite likely not to provide the transport information needed. Often, for example, the results will be required to assess the vulnerability of an aquifer to pollution which may travel many kilometres over periods of years or decades. Clearly, a tracer test carried out within a couple of hours is unlikely to provide estimates of the parameters needed to simulate such long-term behaviour.

7.6 Software

It will often be possible to derive special mathematical solutions, techniques and software. That software is less general than most groundwater transport software and hence more efficient and easier to use. In particular, some of the software performs automatic data analysis (i.e., fitting of models to data by adjusting the transport parameters such as porosity and dispersivity).

A selection of readily-available tracer-test software is listed in Appendix B. However, almost any general-purpose groundwater flow and transport model - which will normally include advection, dispersion and linear sorption - can be used to simulate and interpret tracer tests. That interpretation will probably need to be done by trial and error although there do now exist general-purpose software packages for fitting models to data.

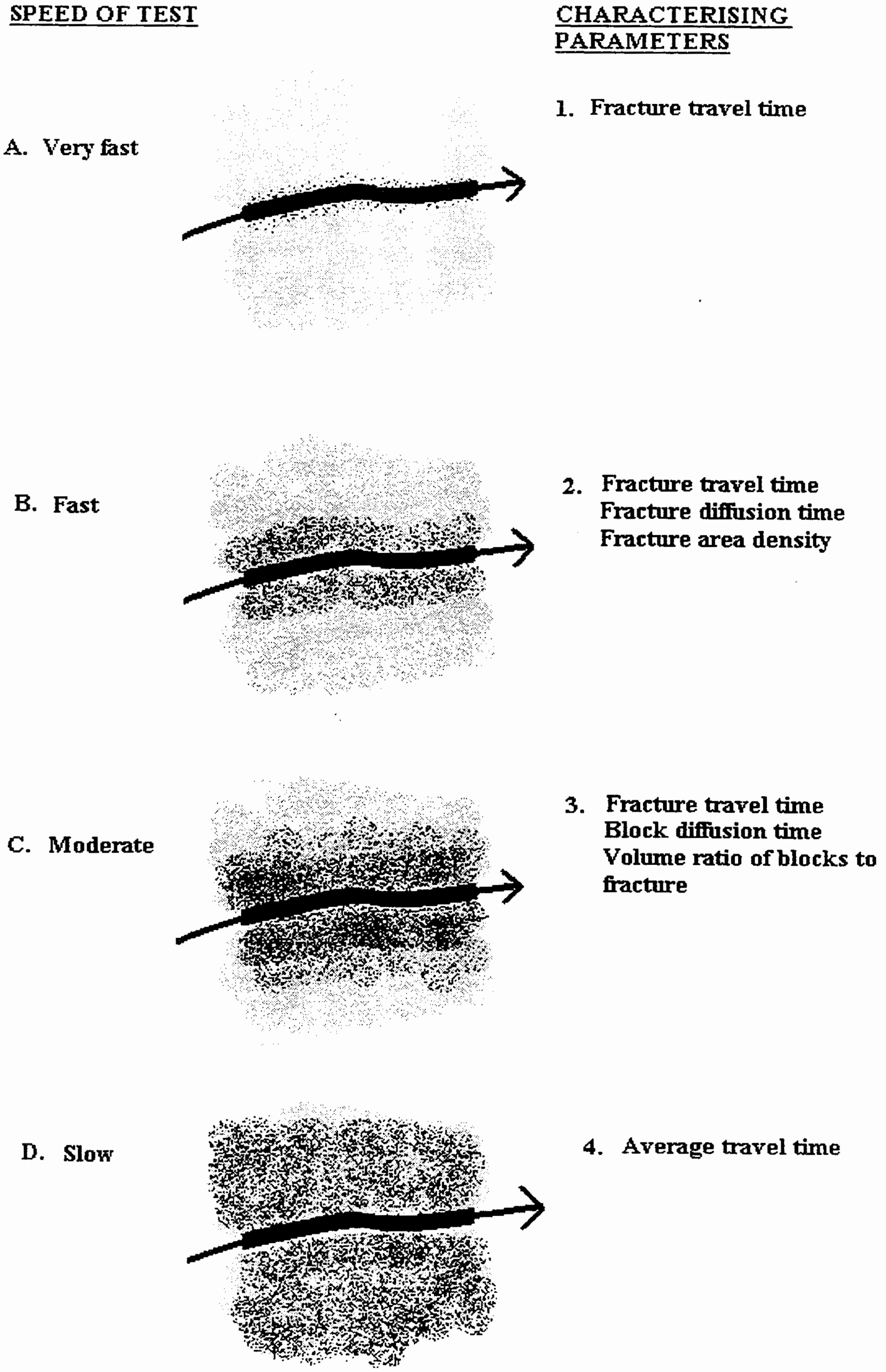

Figure 7.1 Characteristic behaviour and parameterisation for fractured porous rocks. A: Negligible diffusion into matrix, B: Fracture concentration significantly affected by diffusion, C: Diffusion limited by size of blocks, D: Fractures and matrix locally at similar concentrations.

7.7 Data analysis methodology

The following factors need to be considered in deciding what method of analysis, if any, should be applied to tracer test data and how the process should be managed.

- The likely skill of the practitioners of the protocol.
- Whether or not software can be provided.
- Whether all the data for the test are to be recorded or whether the analysis is necessary as a summary.
- What role the analysed results might have in a database of tracer tests.
- Involve the person who will have responsibility for data analysis in the design of the tracer test.
- Use models to help design tracer tests, especially quantity of tracer required and monitoring times and frequency.
- Do not presume that analysis will be possible for all experimental configurations.
- Ensure that any model being used in data analysis is consistent with any model in which derived parameters are going to be used.
- Consider the possibility that others may want to make use of the tests results in the future.
- Recognise the possibility of non-uniqueness in the results.

8 REVIEW OF TRACER TESTS IN THE UK

8.1 Introduction

In the early stages of this project a questionnaire was sent to numerous Environment Agency offices and to selected consultants and Universities. One of the purposes of the questionnaire was to obtain information about tracer tests that had been performed in the Chalk and sandstone aquifers of the UK. A search had shown that very few UK tracer tests were reported in the scientific literature, with the exception of tracer tests in karstic aquifers. The results of the questionnaire were disappointing in that, although most respondents declared an interest in tracer tests very few admitted to having detailed knowledge of actual tests.

The literature search revealed only five published tracer tests. The majority of those which were documented were as unpublished MSc and PhD theses from the Universities of East Anglia and Birmingham. The work of University of East Anglia in particular has influenced the tracer test protocol developed during this project.

8.2 Historical data

Table 8.1 summarises UK tracer test site locations and the aquifers tested. Out of a total of 52 sites identified so far, 41 are in the Chalk aquifer, three in the Triassic sandstone aquifer, four in the Lincolnshire Limestone and two in superficial disturbed material. Figure 8.1 shows the locations of the sites (except for the single site in N. Ireland). It may be seen from the figure that most of the Chalk sites are situated in East Anglia, and these represent the results of research work by the University of East Anglia.

Natural gradient tests have been performed at 34 sites. Forced gradient tests were carried out at 17 sites. At all these sites radial flow tests from an injection borehole to a pumped borehole were undertaken, and in addition at one site flow from a soakaway to a pumped borehole was observed.

A total of 10 tests were undertaken in order to establish groundwater connections. Nine of these were undertaken in Chalk aquifer, of which five were to establish a connection between a swallow hole and spring or borehole. At fifteen sites tests were undertaken to obtain seepage velocities and hydraulic conductivities only (borehole dilution tests). At 25 sites the purpose of the test was to gain an understanding of the groundwater flow mechanisms; at around half of these sites an attempt was made to model the aquifer properties.

Tests in the Lincolnshire Limestone have ranged from small and intermediate scale forced gradient borehole tests aimed at identifying and quantifying the processes which control contaminant migration to allow development and validation of suitable contaminant transport models to natural gradient tests involving transport over distances of several kilometres. The aim of the latter testing was to identify the geological controls on groundwater flow and determine ground water velocity. Test types have included single borehole dilution testing, radial flow testing and sink hole to borehole/spring testing. Many of the tracer tests are unpublished - being tests performed by students from the University of East Anglia and recorded in MSc project reports and PhD theses. The only tracer tests reported in the open literature are those performed at the Longwood Quarry research site where detailed small/intermediate scale tests were performed (Lloyd et al., 1996).

Table 8.1 Summary of historical tracer tests

Site	SiteNo	Aquifer	Grid Reference			Test Type	Tracer	Main purpose of test
Arish Mell, Dorset	1	Chalk	SY	854	807	N.G. BH-spring	Rhod. Ken Acid	Groundwater flow mechanism
Bedhampton Springs	2	Chalk	SU	701	121	N.G. Sw-spring	Rhod. WT	Groundwater connection
Blue Pool	3	Chalk	SU	58	71	N.G. Sw-spring	Fluor.	Groundwater connection
Addington Well, Croyden	4	Chalk	TQ	371	628	N.G. Sw-BH	Salt/Bacteria	Groundwater connection
M1/M25 interchange	5	Chalk	TL	11	03	N.G. Drain-BH	Phot.CU/Bacteriophage/Rhod WT	Groundwater connection
Kilham	6	Chalk	TA	06	64	N.G. BH dilution	Salt	Seepage velocity
Kilham	6	Chalk	TA	06	64	N.G. BH-BH;BH-Sp	Phot.CU/Fluor.	Groundwater connection
Kilham	6	Chalk	TA	06	64	N.G. BH-BH;BH-Sp	Bacteriophage	Groundwater connection
Water End	7	Chalk	TL	23	04	N.G. Sw-spring/BH	Fluor.	Groundwater connection
Horsheath, Cambs	8	Chalk	TL	59	47	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Horsheath, Cambs	8	Chalk	TL	59	47	N.G. BH dilution	Amino-G-Acid	Groundwater flow mechanism
West Wratting, Cambs	9	Chalk	TL	595	518	F.G. BH-BH radial	Amino-G-Acid/Fluor	Groundwater flow mechanism
A604 Junction, Cambs	10	Chalk	TL	5	4	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
Ashdon, Cambs	11	Chalk	TL	575	426	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
Stapleford, Cambs	12	Chalk	TL	47	51	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
Chilford Hall, Cambs	13	Chalk	TL	57	49	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
Fulborn, Cambs	14	Chalk	TL	51	57	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
Linton, Cambs	15	Chalk	TL	540	480	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
New England, Cambs	16	Chalk	TL	5876	6135	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Eagle Lane, Cambs	17	Chalk	TL	625	591	F.G. BH-BH radial	Fluor./Amino-G-Acid	Groundwater flow mechanism
Cambridge Hill, Cambs	18	Chalk	TL	605	569	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Newmarket	19	Chalk	TL	64	67	N.G. BH-Spring	Fluor.	Groundwater connection
Newmarket	19	Chalk	TL	64	67	N.G. BH dilution	Fluor.	Groundwater connection
Corpusti, Norfolk	20	Chalk	TG	11	30	F.G. BH-BH (fail)	Rhod.WT	Groundwater flow mechanism
Candover, Hampshire	21	Chalk	SU	6	4	N.G. BH dilution	Amino-G-Acid/Rhod.WT	Groundwater flow mechanism
Candover, Hampshire	21	Chalk	SU	6	4	F.G. BH-BH radial	Amino-G-Acid/Rhod.WT	Groundwater flow mechanism
Burpham, Sussex	22	Chalk	TQ	0500	0940	N.G. Spring-BH	Fluor./Rhod.WT	Groundwater connection
Swaffham, Norfolk	23	Chalk	TF	8	1	N.G. BH dilution	Amino-G-Acid	Seepage velocity/Hydraulic conductivity
Haskayne Cutting, Lancs	24	Triassic Sandstone	SD	356	090	F.G. BH-BH radial	Fluor./Amino-G-Acid/Bromide	Groundwater flow mechanism
Mersey Tunnel	25	Triassic Sandstone	SJ	33	89	N.G. BH-Tunnel	Fluor.?	Groundwater flow mechanism
Confidential Site	26	Lincs Limestone				N.G. BH-BH	Phot.CU	Hydraulic gradient
Confidential Site	27	Lincs Limestone				N.G. BH-Spring	Rhod.WT/Fluor.	Groundwater flow mechanism
Confidential Site	28	Lincs Limestone				N.G. Sw-BH/Spring/Stream	Fluor./Phot.CU	Groundwater flow mechanism
Waterfoot, N. Ireland	29	Chalk (NI)				N.G. Sw-Spring	Fluor./Rhod.WT/Phot.CU/Dip.	Groundwater connection
Confidential Site	30	Made Ground				N.G. Tank-BH	Fluor./Rhod.WT	Groundwater connection
Well 1, Hockering, Norfolk	31	Chalk	TG	07	12	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
Gt, Ryburgh, Norfolk	32	Chalk	TF	95	27	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
N. Elmham, Norfolk	33	Chalk	TF	98	20	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
Etling Green, Norfolk	34	Chalk	TG	01	13	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
Well 5, Hockering, Norfolk	35	Chalk	TG	06	13	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
Costessey, Norfolk	36	Chalk	TG	17	11	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity

Table 8.1 Summary of historical tracer tests (continued)

Site	SiteNo	Aquifer	Grid Reference			Test Type	Tracer	Main purpose of test
Forncett St. Peter, Norfolk	37	Chalk	TM	16	93	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
Bixley, Norfolk	38	Chalk	TG	25	05	N.G. BH dilution	Fluor.	Seepage velocity/Hydraulic conductivity
Etton, Yorks	39	Chalk	SE	98	43	F.G. BH-BH	Bacteriophage?	Groundwater flow mechanism
Carlton, Yorks	40	Triassic Sandstone	SE	64	23	F.G. BH/Soakaway-BH	Bacteriophage?	Groundwater flow mechanism
Coedely, Glamorganshire	41	Spoil Heap	ST	01	85	N.G. ?	Bacteriophage	Groundwater flow mechanism
Tilmanstone, Kent	42	Chalk	TR	30	51	N.G. Saline Plume	Saline Water	Groundwater flow mechanism
Ten Acre Plantation, Norfolk	43	Chalk	TL	9862	8423	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Snetterton Hall, Norfolk	44	Chalk	TL	9941	9120	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Dower House, Norfolk	45	Chalk	TL	9695	8548	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
South Farm, Norfolk	46	Chalk	TL	9877	8944	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Hockham Hall	47	Chalk	TL	9515	9150	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Roudham, Norfolk	48	Chalk	TL	9638	8722	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Ashdon, Cambs	49	Chalk	TL	576	425	F.G. BH-BH radial	Fluor.	Groundwater flow mechanism
Ness, Yorks	50	Jurassic Limestones	SE	697	786	N.G. BH-BH	Bacteriophage	Groundwater connection
Banterwick Barn, Berks	51	Chalk	SU	5133	7757	F.G. BH-BH radial	Amino-G-Acid	Protocol testing
Heath House, Shropshire	52	Triassic Sandstone	SJ	6028	2459	F.G. BH-BH radial	Amino-G-Acid	Protocol testing

8.3 Tests performed during the project

During the course of the project several tracer tests were performed. There were two main purposes for the testing. The first was to increase the number of recorded tracer tests performed in UK aquifer material. The second was to test the draft protocol prepared at the start of the project and to assess its feasibility in terms of use by 'inexperienced' hydrogeologists.

The testing performed fell into two categories. Two sites were chosen, one on a chalk and one on a sandstone, to perform radial flow tests. These are the sort of tests that needs to be encouraged as they can provide data which will aid parameter estimation for modelling work. Whilst such tests do provide site specific information when properly analysed, it is postulated that the comparison of results from a number of such tests will enable generalised aquifer parameters to be defined.

The other testing carried out was of a more regional scope and is perhaps more indicative of the type of tracer testing which is often contemplated but not often performed. Two tracer test programmes were designed and performed to provide further information about the position of capture zones for boreholes. One site was on the Chalk and the other a Corallian Limestone site. The latter could be considered to be at the 'karst' end of aquifer types, but as the injection and abstraction points were boreholes rather than natural features (such as springs and sinkholes) the techniques and problems are the same as those encountered in the major UK aquifers.

8.3.1 *Radial flow tests*

Chalk site - Banterwick Barn

The difficulties of finding a site suitable for the fieldwork of this project highlights some of the problems that will be encountered if a concerted effort is made to carry out tracer tests to acquire the body of data required for modelling work. One of the main aims of this project is to make it easier to carry out a 'standard' tracer test, by producing a protocol for such a test. However, the problem of finding suitable sites on which to perform these tests has not been resolved. The main requirements for the site were a borehole of sufficient diameter to allow the use of a suitable pump and an observation well within a reasonable distance, which penetrated the same depth as the abstraction borehole. A 'reasonable' distance in this case depends on the aquifer, but 300 m was considered the maximum acceptable distance in the Chalk and 30 m in the sandstone.

Thames Region of the Environment Agency made their River Augmentation Scheme boreholes in the Berkshire Downs available to the project. All these boreholes are equipped with pumps and power and are connected to pipework which eventually feeds into the River Thames or it's tributaries. All of these boreholes had observation boreholes within 300 m but all the observation holes were much shallower than the abstraction holes. It was decided that observation/injection boreholes of a similar depth to the abstraction hole would give the best chance of a successful test and so it was agreed that new injection boreholes would be drilled adjacent to an existing pumping borehole.

After consideration of the various boreholes the Banterwick Barn site was selected. The main reason that this site was selected was because the landowner of the adjacent land was willing to allow further drilling to take place within a reasonable distance of the abstraction borehole. The new injection boreholes were drilled on the side of the track leading past the site (at a distance of ~300 m) and on a piece of waste ground adjacent to the EA compound (about 60 m). This was not ideal spacing but was the best that could be achieved. The borehole drilled at a distance of ~300 m was located along the dry valley in which the abstraction hole was situated in an up- groundwater-gradient direction, whilst the nearer hole was slightly up the side of the valley.

The plan for the site was to perform a radial flow tracer test, injecting different fluorescent tracers at both of the new injection boreholes whilst monitoring the discharge at the abstraction borehole. Salt was added to the fluorescent dyes to allow a borehole dilution test to be performed at the same time as the radial flow test. The addition of salt also permitted confirmation that all the tracer had left the injection borehole. The test procedure was as described in the 'Protocol' in Appendix A.

Practical difficulties were encountered in obtaining permission for the tracer test. This was mainly due to a lack of understanding of the different functions within the Environment Agency. This difficulty led to the formulation of the draft 'standard' letter presented in Appendix A. This letter needs to be submitted to the relevant office of the Environment Agency to obtain permission to undertake a tracer test After these initial difficulties the test proceeded relatively smoothly, despite some problems with the operation of the automatic water sampler used to sample the discharge water.

The data report for the test (Ward et al, 1996) gives the full details of the test. A summary is presented in Table 8.2 and the concentration breakthrough curves in Figures 8.2, 8.3 and 8.4. As can be seen the test from the nearest injection well was repeated. This was because the breakthrough had happened so quickly after the pump was turned on that the details were lost in the 15 minute sampling regime. After the second injection, samples were taken every minute to get better definition. However there is a problem with interpreting the results of this second injection. This is caused by the fact that it takes a finite length of time to remove the injection hose from the borehole (in this case about 10-15 minutes). Thus it is not possible to define accurately the time for the start of the test. This problem is not important when the tracer is injected before the pump is turned-on, or if the travel time towards the borehole is sufficiently long, as would be the case from the more distant injection hole or in an intergranular medium.

The dilution in the injection boreholes showed that the tracer left very quickly (within 30 minutes) from the upper section of the boreholes (35-45 mbgl). All the tracer had left both boreholes within 24 hours after the pump was turned on.

Interpretation of the radial flow test.

Ward (1989) gives details of a technique to analyse breakthrough curves to discover details of porosity and hydraulic conductivity for sets of fractures thought to affect the flow in the aquifer. Outlines of other suitable techniques and models are described in Chapter 7 of this report.

The kinematic porosity of the aquifer is calculated from the peak arrival time. As can be seen this is very low and is indicative of an aquifer with a few fractures which contribute most of the flow.

Table 8.2 Summary of results of tracer test at the Banterwick Barn site.

	BB-South (OBH2)		BB-West (OBH1)
Radial distance	60 m		300 m
Tracer used	50g amino-G acid		100g fluorescein
First breakthrough time	<15 mins	32-42 mins	6 hours
Peak breakthrough time	30 mins	48-58 mins	12 hours
Pumping rate	84 l/s		
Kinematic porosity (%)	0.01	0.02 - 0.03	0.01
Tracer recovery (%)			14

The breakthrough from both injection wells give similar values for kinematic porosity. This implies that the fracture system which dominates the flow in this valley extends over at least 300m.

Further work

The site developed at Banterwick Barn has been used for further tracer tests by MSc students from University College, London (Furey, 1996) and from the University of East Anglia (Parry, 1997). Both of these students performed borehole dilution tests in the new boreholes and the original observation hole at this site. It had been hoped to repeat the radial flow tracer test in 1997 using different pumping rates, but groundwater levels were so low that the Agency would not give permission for groundwater to be abstracted. This is unfortunate as the extra work at the site would have greatly enhanced our understanding of processes which are significant during the course of a radial flow tracer test. The radial flow test reported here was interpreted using the Moench method (Moench, 1989, 1995) by O'Hannely (1997) as part of an MSc project.

The dilution tests, which were carried out with no pumping, showed that there was significant vertical flow in the aquifer which made a conventional analysis, as described in Chapter 6 almost impossible. Parry (1997) has developed a spreadsheet modelling technique which shows some promise.

It is hoped that the site will be used again in the future to develop tracer testing methodologies, and to train hydrogeologists in the techniques of tracer testing.

Sandstone Site - Heath House

A river augmentation scheme site was used to test the tracer test protocol in a sandstone environment. The site used was part of the Shropshire Groundwater Scheme owned and operated by the Midlands Region of the Environment Agency. Two radial flow tests were carried out at different times (Coleby, 1996 and Coleby, 1997).

The Heath House site consists of a 120m deep abstraction borehole and three observation holes - 122m deep at a distance of 10 m, 193 m deep at 20 m and 60 m deep at 100m. Both the abstraction borehole and the 10 m observation borehole were fitted with pumps. This meant that only the 20 m observation hole was suitable for use as an injection hole. The tracer used was Amino-G Acid, which was injected in the top 120 m of the observation hole. As at the Banterwick Barn test, sodium chloride was mixed with the tracer to make it possible to check that the tracer had left the borehole and to enable a crude borehole dilution test to be performed.

The first test was performed at a time when the Groundwater Scheme was being used and so we had no control over the pumping details. This is a good example of a tracer test being carried out in conjunction with other hydrogeological projects. The test was performed by two hydrogeologists who had very little previous experience of tracer testing. They were giving a draft version of the tracer test protocol presented in this report and left to their own devices. An experienced tracer test practitioner was present on site when the tracer test injection was performed to check that everything was done properly and that no problems occurred. Thus this test was a good check on the protocol.

Very few problems were encountered during this test. The protocol was found to be both comprehensive and comprehensible, though it was obviously an advantage that all the necessary equipment for injecting the tracer was available. No difficulty was encountered in obtaining permission to perform the test due to effective liaison between the Agencies water quality and water resources staff.

The breakthrough curve for this test is shown in Figure 8.5 and the results summarised in Table 8.3. There are some anomalous peaks to be seen in the breakthrough curve. These have yet to be explained, but are assumed to be due to contamination.

The second test at Heath House was carried out to see what difference there was in the breakthrough curves when the tracer was injected BEFORE the pump was switched on. The breakthrough curve is shown in Figure 8.6 and the results summarised in Table 8.3 Despite the fact that significantly more tracer was used for the second test the peak concentration of the tracer is not significantly different.

This observation is emphasised when the tracer recovery for each test is compared only one-third of the tracer being recovered in the second test. The reason for this is not known.

8.3.2 *Regional scale tests*

Chalk aquifer - Kilham

The work carried out at this site was targeted towards the verification of the source Protection Zones defined as part of the GPP and is reported fully in Ward and Williams (1996) and Ward et al (1997). This was a phased program of work which included three natural gradient tests between observation hole, using fluorescent tracers and passive, in-situ detectors, and two separate radial test, each involving three separate bacteriophage injections and monitoring at several discharge point, some natural and some artificial. The details of the test will not be reproduced here, rather what follows is a digest of what was learnt about tracer testing during the testing process. The tests were carried out for the Yorkshire Region of the Agency who funded all the drilling operations as well as the purchase and analysis of the bacteriophage tracers.

Table 8.3 Summary of results of tracer tests at the Heath House site

	First test	Second test
Radial distance	20 m	20 m
Tracer used	40g amino-G acid	250g amino-G acid
First breakthrough time	48 hours	60 hours
Peak breakthrough time	100 hours	105 hours
Pumping rate	3.83 Ml/d	3.89 Ml/d
Kinematic porosity (%)	14	13.5
Tracer recovery (%)	93	32

The tracer tests using fluorescent tracers and passive samplers were very successful, proving flowpaths along both dry valleys with travel times of several hundred metres a day. Tracer tests to the public supply well using bacteriophage have also given interesting results. The initial test was from a borehole on the interfluve some 3 km away from the public supply well. The tracer injected at this well was detected (in very small quantities) at a borehole and a spring further down the valley, but not at the pumping well. A new injection well was drilled about 1000 m from the pumping well and the test repeated. This time the bacteriophage was not detected anywhere.

These results are difficult to explain. The pumping schedule at Kilham was not altered during the test and so followed its usual pattern of in-continuous pumping. The geology in the Kilham area is also complicated - geophysical logging suggests that the Chalk dips severely in the vicinity of the pumping station. However, the tracer tests in the dry valleys were successful. This is interesting, as there was no pumping at the detection points, which would have focused the flow towards the boreholes. This leads to the hypothesis that part of the failure to detect phage at the pumping borehole could be something to do with bacteriophage survival - the tests in the interfluves having been performed with fluorescent dyes.

Previous tests in the area with bacteriophage have been successful. Skilton (1986) performed a test at Etton (about 20km away in the same Chalk block). In this test the tracer was detected at the pumping well, albeit at a very low recovery considering that the injection borehole was one of the four wells which forms part of this complex source. Another test in the area, this time in the limestone has also been successful in confirming links from a river to a borehole. However, there is some recent evidence (Rossi et al 1997) that the turbulent flow which occurs in turbine pumps can cause a large number of phage to die (only viable phage can be detected). This needs to be examined further.

Corallian aquifer - Ness

At Ness, the geological and hydrogeological conditions are significantly different to those at Kilham. Ness pumping station abstracts water from Corallian limestone and has a narrow capture zone which extends several kilometres westward and is coincident with the limestone outcrop. The river Rye flows approximately west-east over Kimmeridge and Ampthill clay (below which the Corallian deposits dip) and passes just to the north of Ness pumping station. A series of tracer tests using bacteriophage have been undertaken to evaluate the capture zone of the pumping station and investigate potential contributions of river water to groundwater abstracted.

The initial results have not been promising - none of the injected tracers were detected at the abstraction well. However, investigation of the sampling tap at the well has shown that, under certain pumping conditions, it becomes contaminated with chlorine. This would kill any bacteriophage which were present in the water. This test will be repeated using a new sampling point directly on the rising main.

Before the fieldwork at this site started a sample was taken from the sampling tap to check for the presence of chlorine of which it was found to be free. It was only after the test had failed that a further sample - taken at a different phase of the pumping cycle - was found to be contaminated. The chlorine may not be responsible for the lack of detection at Ness as there is the possibility that the effect of the pump, as postulated for Kilham may be the cause. However, the resampling is an indication of the sort of review that must be carried out when a tracer test is found not to have worked.

8.3.3 *Lessons learnt from field work*

1) Allow plenty of time to obtain permissions from Environment Agency. It is hoped that the availability of this report and the use of a 'standard' letter requesting permission will speed up the process. However, it is advisable to start a dialogue with the relevant Water Quality Manager before planning a test has progressed very far.
2) Data reports should be completed as soon as possible and should contain all relevant data (preferably on a disk). Even though we knew this to be important two of the three data reports for the radial flow tests have missing information. This was usually due to it not being available when the report is compiled.
3) Make sure that the boreholes used are identified correctly. At Banterwick Barn a variety of names were used to describe the boreholes leading to some confusion.
4) It is important to understand the 'plumbing' at abstraction wells. This is especially true if chlorination or blending is practised on site. In some cases it is possible for chlorinated water to flow back down pipework when the pump is not in operation.
5) The regional tests performed during the course of this study were aimed at confirming the position of borehole catchment zones. The difficulties encountered (non-detection of tracer) in these well planned tests show that there are large problems in the use of tracer tests for this purpose. In both cases referred to above, additional injection boreholes were drilled in what were considered on available information to be appropriate places. Despite this investment, and a firm commitment to tracer testing, the results were disappointing and confirm that successful tracer testing to abstraction boreholes over a large distance is complicated. The main lesson learnt from these tests must be that tracer tests may not be the most appropriate tool in these sort of investigations.

8.4 Recommendations for the future.

It is clear from the experience gained during this project that the Environment Agency occupy a central position in the coordination of tracer test knowledge within the UK. Permission to carry out a tracer test must be sought from the Agency Area offices. Thus, it seems that they are the only people who have access to the information required to adequately database all tracer tests.

The Agency is also responsible for approving the quantity and type of tracer to be used. The literature search carried out into tracer properties (Chapter 3) gives the present level of understanding of these issues. It is important that all future developments are monitored and made available nationally.

At present the Agency is only confident about the use of bacteriophage as a tracer towards PWS wells. The problem of phage survival should be examined as soon as possible. The problem is not insurmountable. If it is felt that the phage might die in the pump then it is possible to devise a system in which a small peristaltic pump is lowered into the abstraction borehole near the pump intake to take samples.

The difficulty in using tracer tests to confirm the position of borehole catchment zones encountered during this study re-emphasises the need for good data to be available for modelling work as modelling may prove to be the only appropriate tool for defining such zones. The sort of information that could be gleaned from a widespread programme of radial flow tests could provide a source of data or modelling studies. It seems probable that groundwater models will have to be used in a more statistical approach than is presently common practice, to produce a range of possible catchment areas.

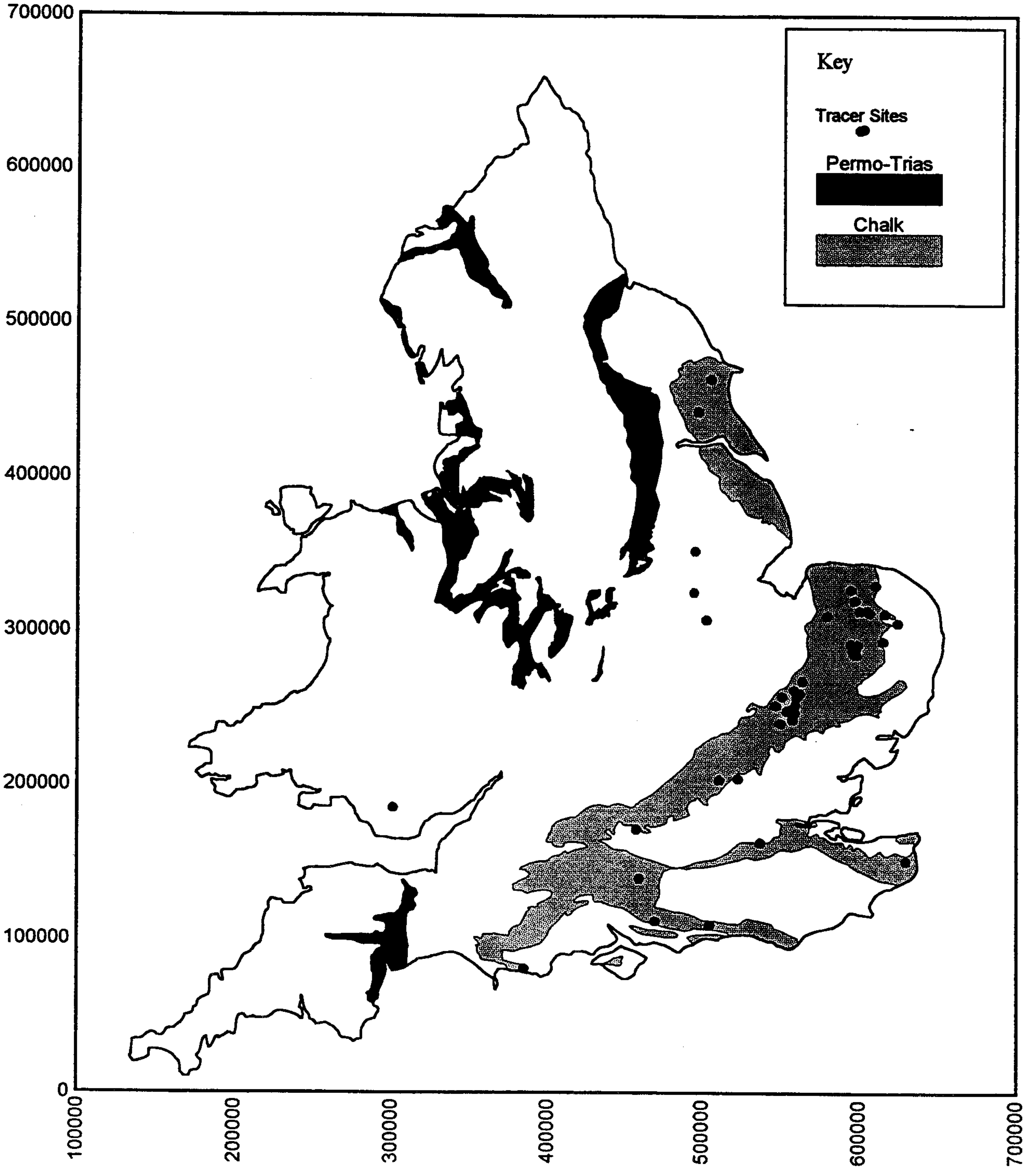

Figure 8.1 Tracer test sites in England and Wales. This figure shows the outcrop of the Chalk and Permo-Triassic sandstone aquifers.

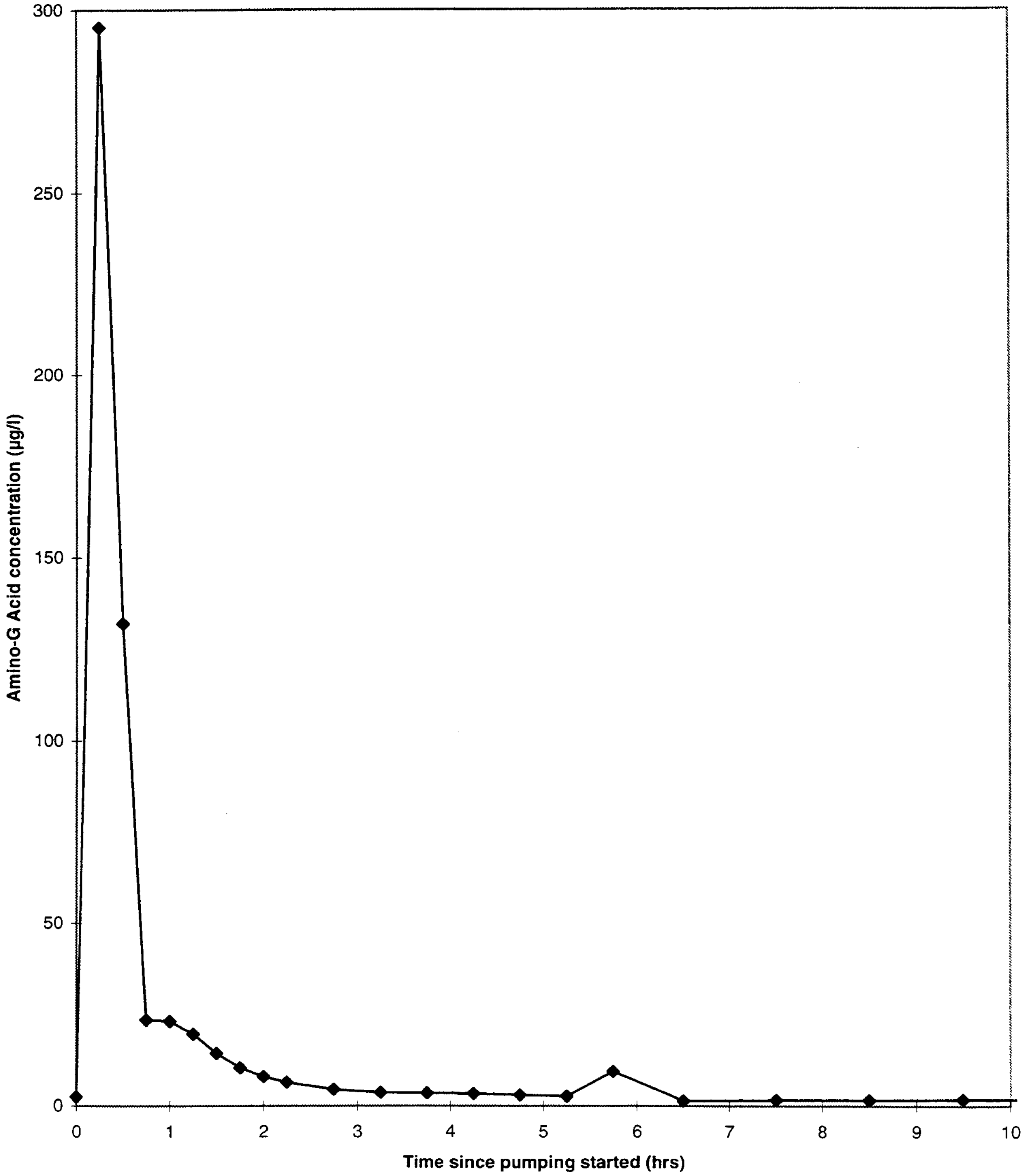

Figure 8.2 Concentration breakthrough curve for initial injection in BB1

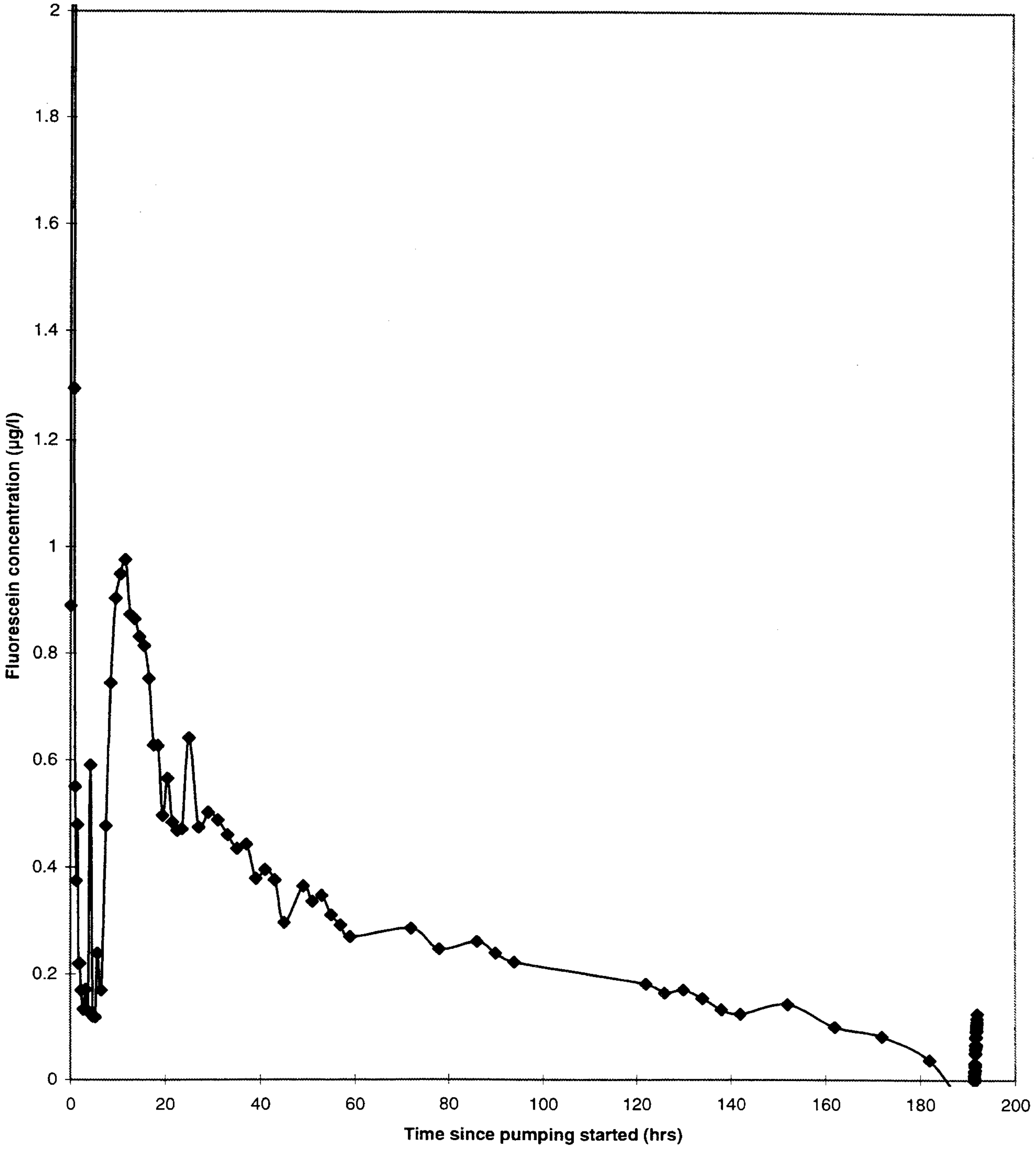

Figure 8.3 Concentration breakthrough curve for initial injection in BB2

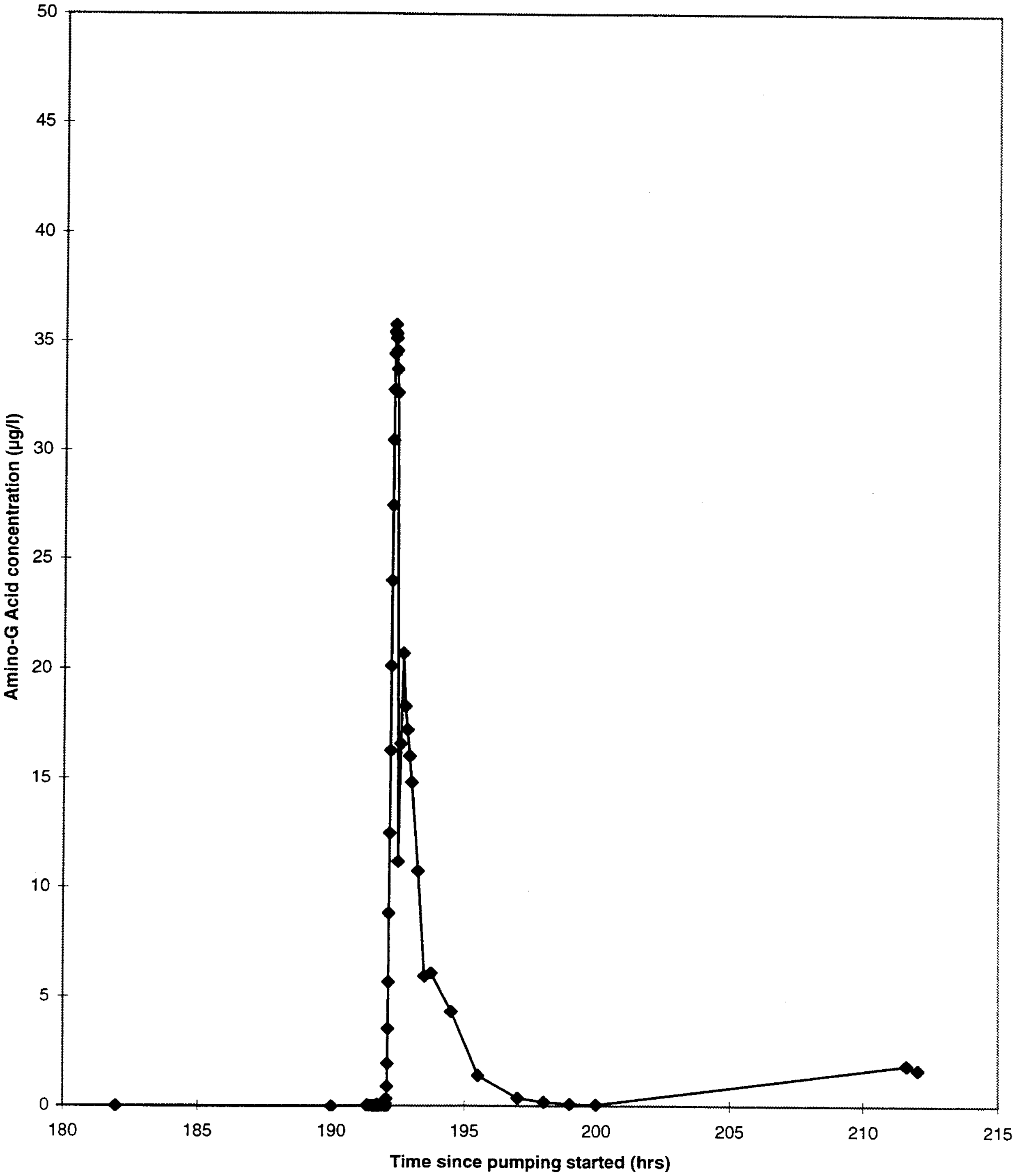

Figure 8.4 Concentration breakthrough curve for second injection in BB1

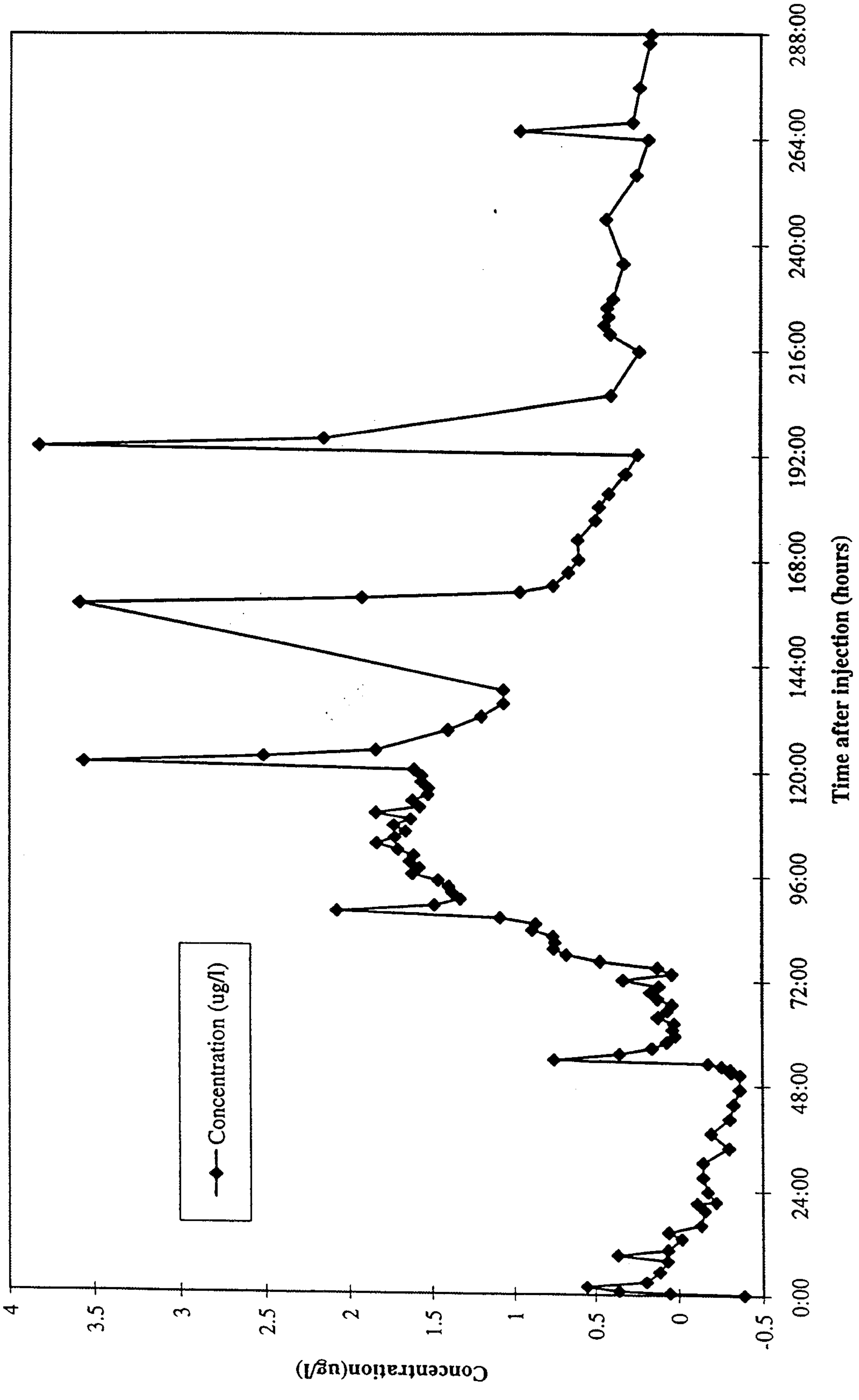

Figure 8.5 Concentration breakthrough curve for first test at Heath House

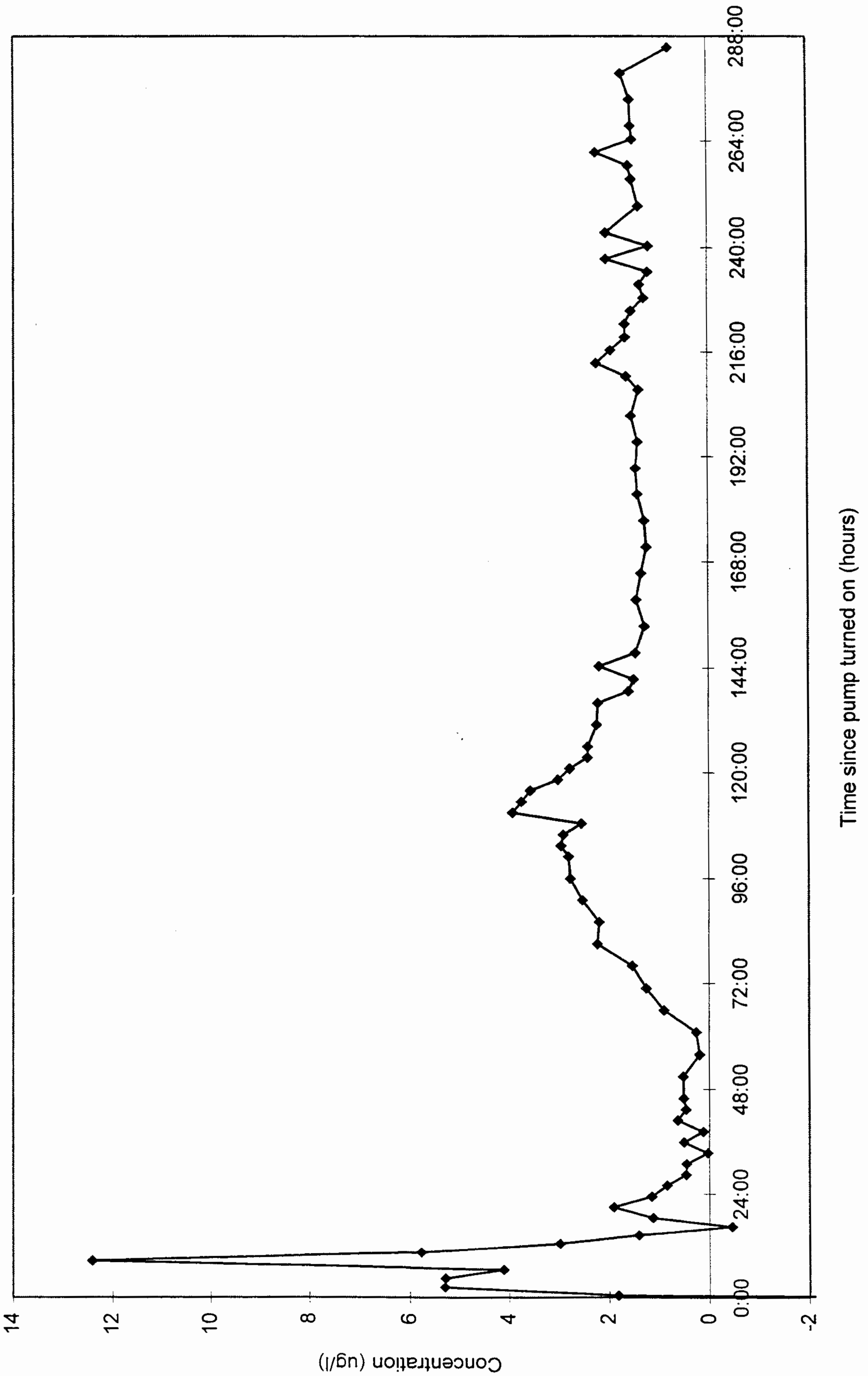

Figure 8.6 Concentration breakthrough curve for second test at Heath House

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APPENDIX A

PROTOCOL FOR BOREHOLE TRACER TESTS

A.1 General principles

A tracer test is a means of studying the behaviour or movement of water or a contaminant within the sub-surface. It involves the addition of a distinguishable material (tracer) to the groundwater system which has nearly identical properties to the substance being studied. This substance could be water, where a flow path is to be proven, or an organic contaminant which has accidentally entered the groundwater system and its behaviour must be determined. The movement of the tracer, which is controlled by the aquifer properties, is then monitored by sampling and analysing groundwater extracted from boreholes, springs, streams etc. along or at the end of the subsurface flow path. From the data obtained, a wider range of aquifer and transport properties can be determined than by any one other hydrogeological investigation technique.

Results can be used to predict travel times of contaminants, likely dilutions, residence times, determine effective porosity, retardation properties and the effects of heterogeneity on contaminants. In addition, hydraulic conductivity, fracture apertures, fracture spacings sizes and matrix diffusion can be obtained where appropriate techniques are used.

Tracer tests, like pumping tests, can be expensive, requiring adequately screened and developed pumping and observation boreholes, suitable pumping, injection, sampling and analytical equipment, support equipment and personnel.

It is desirable therefore that a suitably designed and considered test programme is developed before attempting to carry out a tracer test. This requires a detailed desk study of geological, hydrogeological, geographical and geochemical properties of the study area and a clear understanding of what can be achieved.

Groundwater conditions should reflect normality unless otherwise required, e.g. solute migration under high water table conditions. There should also be no artificial controls on groundwater flow other than those imposed for the purposes of the tracer test or those being specifically studied.

A number of alternative borehole tracer test methods are available. These range from single hole techniques which investigate only a limited volume of aquifer and yield only limited information on the aquifer to multi-well methods which can be more complex, likely to be more expensive, time consuming and require larger quantities of tracer. They will however yield far more information on the aquifer, groundwater flow and contaminant transport.

The choice of tracer test will depend on the purposes of the investigation (aquifer properties, contaminant transport, proving a connection, flow direction etc.), the available resources (financial, staff, expertise and boreholes etc.), practical consideration (borehole access, choice of tracer, time scales etc.) and any restriction imposed (e.g. tracing to a public water supply well).

Where appropriate, it is recommended that an aquifer pumping test be conducted within the same borehole array as the tracer test (BS 5930). For certain tests (radially converging and pump and drift back) the pumping test can be run in parallel. For others (borehole dilution and radially diverging) it is recommended that the pumping test is performed after the tracer test to remove the tracer from the aquifer.

Analysis of data from a tracer test varies in complexity depending on the test method chosen and the purpose of the test. Care should be taken, when designing the test, to ensure the correct measurements are taken to enable a full interpretation of the results to be made. Where necessary expert advice should be sought on application of complex models for interpretation.

A.2 Single Borehole Dilution Tests

This type of relatively simple tracer test requires the use of only one open or screened borehole.

The value of the test in terms of aquifer transport properties is somewhat limited in that it only investigates a small volume of aquifer material and can only be used, on its own, to determine Darcy velocity. In order to determine flow velocity, knowledge of kinematic (dynamic) porosity is required and for hydraulic conductivity, the hydraulic gradient.

This single-borehole test is useful in providing basic information for the planning of more complex tracer tests, the results of which, when combined, can yield valuable flow properties.

By monitoring the dilution of tracers over time at different depths, a vertical velocity distribution may be obtained if groundwater flow across the borehole is horizontal. However, if excessive vertical head gradients exist, the calculated velocity values will be invalid. In this case, dilution profiles may only be used to indicate potential inflow/outflow points and relative variations within the borehole. Vertical gradients may occur in deep boreholes or those in fractured rock.

A.2.1 *Boreholes*

For a single borehole dilution test a single borehole is required. The minimum requirements are that the borehole is of sound construction, is fully screened/open and fully penetrates the aquifer unit being investigated. Ideally, the borehole will not penetrate more than one aquifer unit which may result in vertical flows within the borehole.

The diameter of the borehole should be as small as possible but large enough for insertion of the injection equipment and sampling device. The borehole has the effect of distorting the groundwater flow and so minimising its diameter reduces this effect. Practically, for major aquifers, a 100 mm diameter borehole is adequate but larger boreholes can be used.

Details of the borehole should be examined to determine: borehole depth, diameter(s), casing and screen construction, verticality, geology, water level (and fluctuations) and water quality. Where practical, a suite of fluid and formation geophysical logs should be run. This will allow better planning of the test and make test interpretation much easier.

The condition of the borehole should also be checked to ensure that it is as recorded on the borehole completion details. Any changes should be investigated, e.g. changes in borehole depth may result from collapse or blockages. CCTV and caliper logging can be used to inspect the borehole and check the diameter. Other equipment to be used during the test should also be checked.

Before starting the tracer test, background samples of groundwater should be taken from the test borehole to determine the background presence and concentration of the proposed tracer. Ideally, the borehole should be monitored for variations in background concentration over a period of similar length to that of the test.

A.2.2 *Tracer injection*

The volume of water in the injection borehole should be calculated by multiplying the height of the column of water in the borehole (total depth of borehole minus depth to water) by the cross-sectional area of the borehole.

The average background concentration of the chosen tracer in the groundwater should be determined from the pre-injection measurement suite (see above).

The amount of tracer required should be calculated by determining the initial concentration required in the borehole immediately after injection. This is done by taking the background concentration or minimum detection limit (whichever is the greatest) and multiplying it by 100. This value is then multiplied by the volume of water in the borehole (calculated above).

The tracer should then be prepared by calculating the volume of water contained in the injection hose opposite the open/screened section of the borehole after the hose has been lowered into the borehole (V1) (see Figure A.1). The length chosen for the volume inside the hose should be adjusted by subtracting the distance between the base of the weight and the end of the hose plus 100 mm. This is to ensure that excessive tracer does not accumulate at the bottom of the borehole (which is often a stagnant zone) and allows consideration of the weight attached to the hose. Additionally, where a significant length of unslotted casing is below water (a potential static flow zone), the volume of water contained within this section of the injection hose (V2) also needs to be calculated.

The mass of tracer should then be dissolved into the calculated volume of water in the hose within the uncased or screened portion of the borehole, preferably previously extracted groundwater. Where the volume of water is too small for dissolution of all of the tracer (the solubility of the tracer in water should be known), the volume of water may be increased in increments equal to the initial volume. Each increment is then injected separately following the procedure below. Alternatively, where the of tracer is already in liquid form, it may be necessary to add water to make up the volume.

A suitable injection hose should then be prepared. The hose can be a standard 10 mm diameter garden hose (or similar) which should be of a length 100 mm longer than the total depth of the borehole. Where joins are required, these should be made using connectors which can take a load. An ideal connection can be made using plastic barbed inserts and jubilee clips (or similar).

At the lower end of the hose, a weight should be attached by using a metal/plastic insert in the end of the hose and securing the weight using a jubilee clip (or similar). This end of the hose should remain open and not be restricted. The weight diameter of the weight must be less than the injection borehole diameter and ideally be slimline so that is unlikely to catch on screen, casing or aquifer material when in the borehole (Figure A.1).

In addition to the weight, the positioning of an inverted plastic funnel with holes drilled in the sides and of a diameter 4-5 cm less than the borehole diameter just below the open end of the hose should be attached (Figure A.1). This improves the mixing of the tracer in the borehole as the hose is removed (see below). For the other end of the hose, another metal insert is required and a borehole clamp (adequate for the size of injection borehole chosen) should be prepared (Figure A.1).

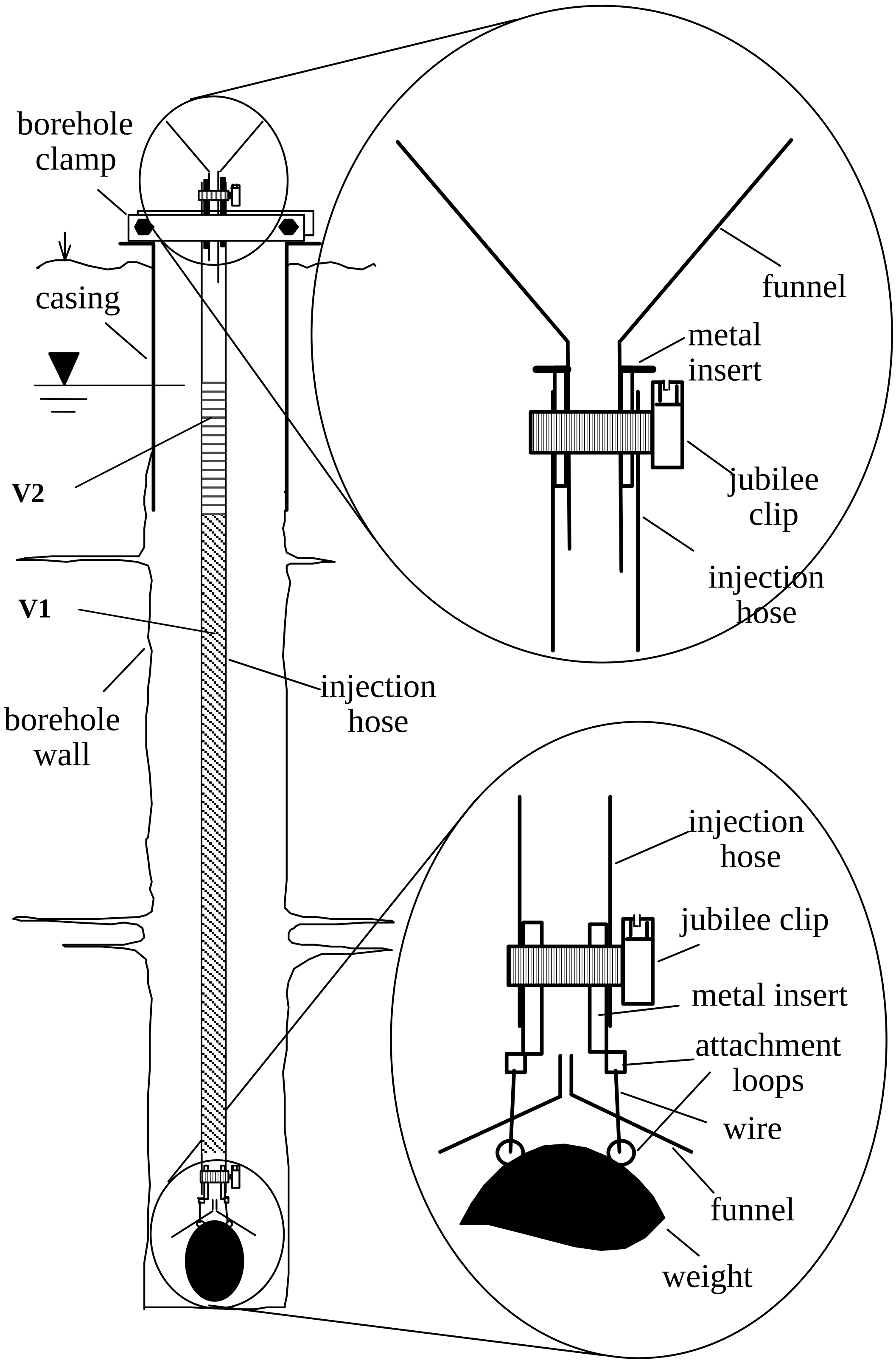


Figure A.1. Schematic diagram of injection borehole assembly

After collection of a background suite of samples or borehole logs to determine the initial concentration distribution, the hose should be lowered down the borehole until the weight rests on the bottom. The injection hose length can then be trimmed so that the borehole clamp can be attached to the hose and the assembly rested on the top of the borehole casing.

A funnel should then be inserted into the top of the hose (ensuring that a gap is left to allow air to escape). A short length of narrow diameter tube inserted into the top of the hose along with funnel is satisfactory.

Tracer should then be poured slowly down the injection hose so that air within the hose is allowed to escape. Care must be taken to avoid spillage and contamination. Any spillage should be mopped up with absorbent material and then areas decontaminated. This should be followed by a volume of water (preferably previously extracted groundwater) which is equal to the volume of water in the hose within the cased part of the hole if this necessary (see above)

It is strongly recommended that protective (disposable) clothing and gloves are used during injection.

It is recommended that a ‘dummy-run’ is made with a simulated injection being performed using water as a substitute for the tracer in order that the operator(s) may become familiar with the procedure and any problems can be solved.

After completing the injection of tracer into the hose, approximately 5 minutes should be allowed for any residual tracer to run down the inside of the hose and water levels to equilibrate. The groundwater in the hose opposite the open/screened section of the borehole should all have been displaced by the tracer.

The hose should then be withdrawn from the borehole, after removing the funnel, at a rate of no more than 2 m per minute. As the hose is pulled, the tracer will exit from the bottom of the hose leaving a column of tracer of uniform concentration within the borehole. The inverted funnel and weight at the base of the assembly will have mixed the tracer with the water in the borehole.

The time at which hose withdrawal began and its completion should be recorded.

After completion of the withdrawal of the hose, the injection equipment should be removed with care for decontamination and cleaning. Ideally the equipment should be bagged and removed from the site until it can be treated.

Immediately after injection, a suite of samples/measurements should be taken to ascertain the initial concentration distribution within the borehole.

A.2.3 *Tracer sampling*

Depending on the type of tracer used, a suitable sampler should be chosen to provide an initial concentration profile and monitor the subsequent dilution of the tracer in the injection borehole. If an electrolyte (salt) tracer is used, a logging conductivity probe may be used. Alternatively a suitable water sampling device (depth sampler) should be used.

The locations for sampling should be considered carefully if a continuous logging probe is not being used. As a minimum requirement, 20 uniformly spaced samples should be taken within the borehole water column. This may be modified or supplemented by additional samples taken from locations adjacent to zones of interest identified from geological/geophysical logs.

It is important that sampling locations are clearly defined at the outset and recorded so that repeat samplings can be made and the time of sampling recorded.

Where groundwater samples are to be extracted, the most suitable method is by use of a discrete depth sampling bailer. The bailer should be of narrow diameter relative to the borehole diameter but be capable of containing sufficient sample volume for analytical purposes. The volume required should be determined after consultation with the analyst(s). The narrower the diameter of the bailer and the more streamlined its design, the less mixing it will cause in the borehole when being lowered or raised. It must also be capable of taking discrete depth samples and have some mechanism for determining its depth to centimetre accuracy. Both a manually or automatically lowered device is acceptable although the speed of vertical movement should not exceed 10 m per minute.

Samples should be taken from each selected depth in a downward sequence, i.e. the uppermost sample should be taken first. The sample withdrawn from the borehole should be immediately transferred to a suitable sample storage container and stored as appropriate for the type of tracer. The time of sample collection should be recorded.

Samples should then be transferred to the laboratory or analysed on site as soon as is practically possible.

Where continuous downhole monitoring is being performed, the data should be recorded and processed as soon as possible. Any calibrations required for depth or concentration measurements should be immediately applied where possible. In all cases times of start and end of a logging run should be recorded as well as the logging speed.

The recommended data sheet for recording the required data is shown in Figure A.2.

A test should continue until the average concentration of tracer within the borehole is less than 50% of the original concentration, and preferably less than 20%. The time required to reach this concentration depends on the groundwater velocity. After the first sampling run, immediately after injection, a second set of samples should be taken after 30 minutes. This should provide an indication of dilution rates through observed colour changes or by concentration change. An appropriate sampling frequency can then be determined.

A minimum of five sample runs should be performed after the injection to enable an adequate dilution profile to be obtained, but preferably the number should be greater than this

It is important for the interpretation of the test results that each vertical profile of tracer concentration is taken over as shorter time as possible but without causing any disturbance within the borehole which would adversely affect the results. Therefore care should be taken in following procedures which will cause minimum disturbance such as sampling from the top downwards.

A.2.4 *Interpretation of results*

The following data are required: tracer concentrations in groundwater, times of sampling after injection and depth of sampling. The tracer concentration should be used to calculate C/C_0 at each time increment by dividing the measured concentration (C) by the initial concentration (C_0) at time zero, immediately after injection.

Single borehole dilution tracer test

Ground level [GL] (m OD):
Casing Top [CT] (m OD):

Depth below casing top to:
- bottom of borehole (m):
- bottom of casing (m):
- initial rest water level (m):

Borehole diameter (m):

Site:
Location:
Borehole No:
NGR:

Tracer injected:
Mass injected:
Initial conc.:

Time/Date start of inj.:
Time/Date end of inj.:

† Datum: [OD] / [CT] / [GL] (delete as appropriate)
^ Concentration: [ppb] / [ppm] / [Bq/l]/ other [................] (delete as appropriate)

Location/Depth (mbd)†	Sample 0 Time/Date	(Background) Conc(........)^	Sample 1 Time/Date	Conc	Sample 2 Time/Date	Conc	Sample 3 Time/Date	Conc	Sample 4 Time/Date	Conc

Figure A.2. Recommended data sheet for borehole dilution test.

The data should be plotted graphically on semi-logarithmic axis, depth (y-axis) against concentration (log x-axis) with samples taken at each sampling event represented by the same symbol (Figure A.3). All sampling events showed be represented on the same plot. This allows an indication of the vertical variation in dilution and identification of rapid/static flow zones.

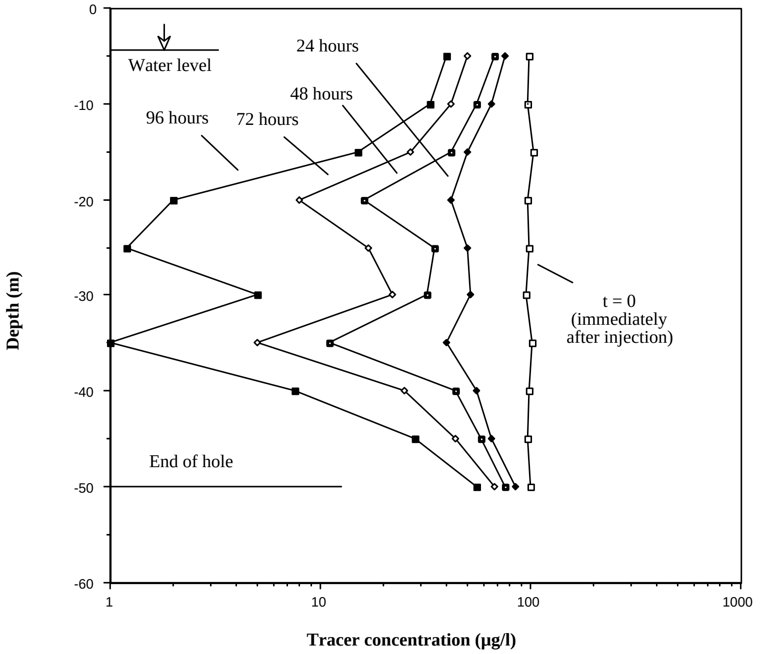


Figure A.3. **Vertical distribution of tracer at different times after injection.**

Dilution of the tracer should be exponential with a time constant related to specific discharge (see Appendix B). The Darcy velocity at different depths can be determined by plotting the data for each sampling point semi-logarithmically with time on the x-axis and C/Co on the logarithmic y-axis. On each graph, the data from one measuring point should be plotted (Figure A.4).

Calculation of seepage velocity, q, can then be made by fitting a straight line through the data points and using the following equation (see Appendix B):

$$q \approx 1.8rA \qquad \text{(A.1)}$$

where r is the borehole radius and A is the arithmetic slope of the straight line, b/a in Figure A.4.

Groundwater velocity may be calculated if kinematic porosity is known by dividing the seepage velocity by the kinematic porosity and hydraulic conductivity determined if the natural hydraulic gradient is known

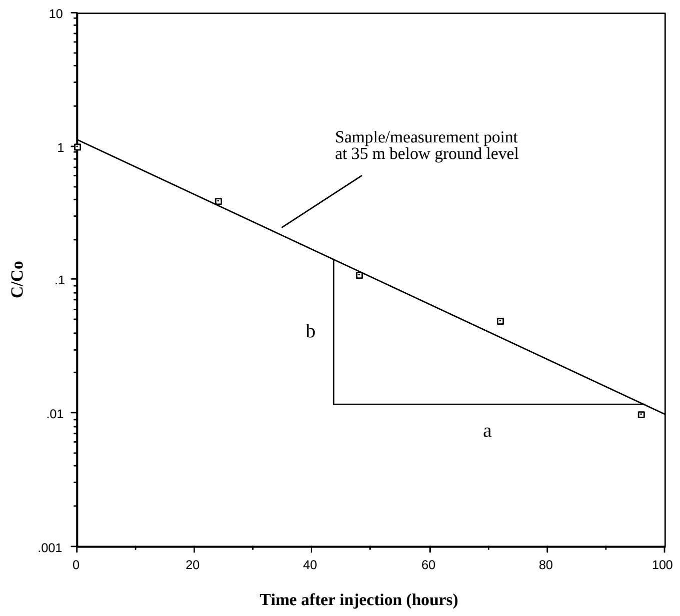


Figure A.4. Dilution measurement at one sampling point over time.

A.3 Radially Converging Tracer Tests

The borehole configuration requirements of this test are similar to those of the pumping test. A minimum of two boreholes, one suitable for pumping and the other, within the cone of depression of the pumped well, for monitoring/injecting tracer.

One of the wells (usually the central borehole of an array or the one with the largest diameter) is pumped at a constant discharge rate and tracer is injected into one or more of the other boreholes after pseudo steady-state conditions have been achieved (when the head differences between the boreholes are nearly constant).

Tracer arrival at the abstraction well and its disappearance from the injection well(s) are monitored over time during the period of pumping.

Pumping should continue until all of the tracer has been recovered or concentrations of tracer in the injection borehole and sampling well have returned to background. The discharge rate should be measured regularly throughout the test and recorded. Ideally measurement of total volume pumped should also be recorded if possible.

This forced gradient tracer test can provide information on aquifer structure, kinematic porosity and contaminant behaviour if successfully applied.

It is recommended that an aquifer pumping test be run along side the tracer test, for example following the British Standard (BS 5930).

A.3.1 *Boreholes*

The pumped well should be of sufficient diameter to permit the insertion of a rising main and pump of a suitable type and capacity, together with a standpipe and velocity/flow meter. The borehole should be of adequate construction and fully penetrate the aquifer (or aquifer unit) being tested.

A suction pump may be used where minimum water levels are no lower than 5 m below the pump or alternatively (and more usually) a submersible pump may be used. An approximate guide to pump sizes and maximum discharges is shown in Table A.1.

It is essential that a constant and sustainable flow rate is achieved. The flow rate must be adequate to develop a cone of depression within the aquifer which does not de-water the abstraction borehole (or pump) but extends beyond the injection borehole(s). An estimate of the required discharge for a particular steady-state drawdown can be made using the following equation, based on the size of the borehole capture zone:

$$Q = \pi R T i \qquad \text{(A.2)}$$

where R is the distance between the boreholes, T is the aquifer transmissivity and i is the regional hydraulic gradient.

The injection borehole(s) which can double as a water level monitoring borehole(s) should have similar depths to the abstraction well, or penetrate the same aquifer (or unit).

The diameter of the injection borehole(s) should be as small as possible but large enough for insertion of the injection equipment, sampling device and water level monitoring equipment. Practically, for major aquifers, a 100 mm diameter borehole is adequate but larger boreholes may be used.

Table A.1. Approximate borehole sizes required for different discharge rates.

Discharge range (m^3/h)	Minimum diameter (mm)
0.5 - 5.5	100
4 - 11	100/150
22 - 56	150
50 - 90	200
90 -160	250

Available details of the boreholes should be examined to determine: borehole depth, diameter(s), casing and screen construction, verticality, geology, water level (and fluctuations) and water quality.

The condition of the borehole should also be checked to ensure that it is as recorded on the borehole completion details. Any changes should be investigated, e.g. changes in borehole depth may result from collapse or blockages. CCTV and caliper logging can be used to inspect the borehole and check the diameter. Ideally, where possible, a full suite of fluid and formation geophysical logs should be obtained. Other equipment to be used during the test should also be checked and rest water level recorded.

Before starting the tracer test, samples of groundwater should be taken from the test boreholes to determine the background presence and concentration of the proposed tracer(s).

A.3.2 *Tracer injection*

The majority of the steps carried out in injecting tracer are identical to those for a single borehole dilution test (Section A.2.2) with the following differences:

A measurement of the water level is required at maximum drawdown (steady-state).

The abstraction well discharge water should be sampled during the period before steady-state and analysed to characterise any temporal variations in background concentration. If background concentrations are high or considerable variation is present an alternative tracer should be considered.

The mass of tracer required for each injection should be calculated using any available historical data for tracer testing locally or by using the following procedure:-

1. The optimum amount of tracer is that which will result in a peak concentration which is 10 to 100 times the background concentrations at the sampling point(s). This allows detailed definition of the breakthrough curve including time of first arrival and the peak.

2. The simple formula below, based on one-dimensional Fickian dispersion can be used to estimate the minimum mass of tracer required. It uses estimates of dispersivity, α, the cross-sectional area of the injection pulse, A, distance between injection and sampling points, r and the maximum peak concentration, c_m to estimate the mass of tracer, M, required for injection;

$$M = c_m A \sqrt{4 \pi r \alpha} \qquad \text{(A.3)}$$

For radially converging tests the effects of radial flow may result in the mass calculated in equation A.3 underestimating the mass required. To take account of the radial flow the mass obtained, *M*, should be multiplied by factor equal to the kinematic porosity, n_e multiplied by the circumference of the circle of radius, *R* equal to the distance between injection point and sampling well divided by the diameter, *d* of the injection well to determine an upper limit for the mass of tracer, M_2 needed for a radial test ;

$$M_2 = M \times \left(\frac{n_e 2 \pi R}{d} \right) \qquad \text{(A.4)}$$

3. Where tracers which undergo decay (phage and radioisotopes) or sorb are used a correction should be considered for this when calculating the mass required.

4. The value for dispersivity can be approximated as one tenth of the scale of the investigation, i.e. one tenth of the distance between injection and sampling points.

A.3.3 *Tracer sampling*

For sampling of the injection borehole(s), the procedure described in the single borehole dilution section (Section A.2.3) should be employed.

Tracer dilution can be expected to be more rapid than would occur during the single borehole dilution test due to the artificially induced gradient. Sampling frequencies may therefore need to be much more rapid if the dilution profile is to be well defined.

Because of the high concentrations of tracer present in the injection borehole, especially at the start of the test, extreme care should be taken to avoid possible contamination of samples from other boreholes. If possible each borehole should have a dedicated sampler and protective clothing should be worn when sampling.

It is likely that dilution of the injection borehole samples will be required in some cases prior to analysis because of the high concentrations involved. Any dilutions which are necessary should be done with care using accurate equipment and all dilution details recorded accurately and the original sample retained. It may be necessary to designate separate areas in the laboratory for the preparation and dilution of tracers and the analysis of samples to avoid contamination.

The discharge well should be sampled by collecting appropriate volumes of the pumped water and storing them in appropriate storage containers for the tracer being used. The time and date of sample collection should be recorded as well as the time after start of injection.

Either manual or automatic sampling may be employed. Ideally, automatic water samplers should be used. These can be programmed to collect up to 24 samples before requiring servicing. It will be necessary to have spare fully-charged batteries, replacement bottles and ideally a stand-by sampler to ensure trouble free operation.

Where automatic samplers are employed, the contents of the sampler containers should be rinsed out thoroughly after transferring the sample to an appropriate storage container to avoid carry-over contamination. Alternatively additional sets of numbered bottles could be obtained for the automatic water sampler to enable for effective cleaning before re-use.

Manual sampling whilst possible, may require long term attendance and provision for 24-hour a day working.

The minimum frequency of discharge borehole sampling (manually or automatically) is shown in Table A.2.

Samples should be transferred to the laboratory or analysed on site as soon as is practically possible.

The recommended data sheet for recording details is shown in Figure A.5.

Table A.2 Recommended sampling frequency.

Time after injection (h)	Sample frequency
0 - 6	15 mins
6 - 12	30 mins
12 - 72	1 hour
72 - 120	2 hour
120 - 240	4 hour
240 - 360	6 hour
360 +	8 hour

Radial injection tracer test

Site:
Location:

Injection borehole details
Borehole No:
NGR:
Ground level [GL] (m OD):
Casing Top [CT] (m OD):

Depth below casing top to:
  bottom of borehole (m):
  bottom of casing (m):
  initial rest water level (m):

Borehole diameter (m):

Abstraction borehole details
Borehole No:
NGR:
Ground level [GL] (m OD):
Casing Top [CT] (m OD):

Depth below casing top to:
  bottom of borehole (m):
  bottom of casing (m):
  initial rest water level (m):

Borehole diameter (m):

Tracer injected:
Mass:
Time/Date start of inj.:
Time/Date end of inj.:

^ Concentration: [ppb] / [ppm] / [Bq/l]/ other [................] (delete as appropriate)

Time after injection (h)	Concentration ^	Time after injection (h)	Concentration ^	Time after injection (h)	Concentration ^

Figure A.5. **Recommended data sheet for radial tracer test.**

APPENDIX B

MODELS AND SOFTWARE FOR ANALYSING TRACER TESTS

B.1 Introduction

This appendix is provided for the benefit of those who are involved in the analysis of tracer tests and hence are concerned with the details of the theory, mathematics and software. It is assumed that the reader has some experience in groundwater modelling but may never have specifically been concerned with tracer-test interpretation.

There have been many reviews of the modelling in relation to tracer tests. In 1984 the International Atomic Energy Agency convened an advisory group meeting on *Mathematical Models for Interpretation of Tracer Data in Groundwater Hydrology*. The meeting resulted in a publication by the same name (IAEA, 1986) which comprises eight review papers and conclusions with a critical review. Mathematical modellers should find this a particularly valuable review to that date.

Many of the publications listed in the bibliography of this report relate to modelling and the reader is encouraged to scan that list if the topic of interest is not covered below.

B.2 Time concepts in tracer theory

A quantity of tracer entering a real hydrogeological system over a short period of time will leave the system over a much longer period of time. The time spent by any single particle (or molecule) in the system is referred to as its *transit time* or *residence time*. Transit times in groundwater systems from recharge to discharge to surface water can be from hours to many thousands of years. The distribution of transit times is a result of dispersive processes discussed in Section 2.3 of this report.

The time that the particle has spent in the system is usually referred to as an *age*. The age will be less than the transit time except at the instant when the particle exits the system, when the two are equal.

Water also consists of molecules, each of which can be characterised by an age, while in the groundwater system, and a transit time. It is often forgotten that water molecules are subject to the same dispersive processes as tracers and therefore molecules found alongside one another may have very different ages and the meaning of terms such as ‘age of the water’ need clarification.

Particular problems arise in fractured porous systems and particularly in relation to isotope dating (Barker 1993). For example, Neretnieks (1981) uses the term "residence time of the water" to refer to the mean travel time of water in the fractures, which may be orders of magnitude different from the average time that water molecules spend in a system such as a chalk aquifer. This discrepancy arises because water molecules diffuse from fractures into relatively immobile pore water, they therefore have an average speed determined by the relative times spent in the fractures and matrix pores.

In general, it is necessary to be careful in interpreting any reference to age and often necessary to interpret such statements in relation to some model of the system.

B.3 Distributed sources and variable flow systems

Environmental tracers (e.g. tritium) do not enter a groundwater system in the same manner as artificial tracers: the flow system is not controlled and will, in general, vary. Maloszeweski and Zuber (1982) present transit time functions for simple distributed sources. Zuber (1986) presents solutions which can be applied to variable flow systems with constant volume or constant turnover time.

A relatively simple numerical technique known as multi-compartmental modelling (e.g. Adar and Sorek, 1989) can be applied more generally than analytical solutions to environmental tracer problems.

B.4 Tracer test boundary conditions

Given that tracer tests are intended to be particularly carefully performed and analysed experiments, it is appropriate that care is taken in defining precisely the boundary conditions. Kreft and Zuber (1978) consider a variety of possible conditions; for example, the detection method may give a concentration averaged over a cross section or over the flux of water. (Much of the following is adapted from papers by Zuber and his collaborators.)

The precise meaning of the term ‘concentration’ needs careful consideration in (dynamic) tracer systems and that a variety of mathematical definitions are possible, depending on the circumstances of tracer injection and detection. The term ‘resident’ concentration (c_R) is used for the ratio of tracer mass to the volume of fluid in which it is contained at a given time. This is the more common definition of concentration. The term ‘flux’ concentration (c_F) is the ratio of the mass of tracer passing through a given cross-sectional area to the volume of fluid passing through that area in the same time. These definitions can be made mathematically precise by letting volume, area and time of observation tend to zero, although in practice these are always finite.

These two definitions can refer, in a tracer test, both to the tracer input and the tracer detection. In addition, tracer input is normally controlled to be either (approximately) instantaneous or continuous. Therefore a comprehensive notation requires three characterising parameters and the observed concentration can be written as C_{ABC} where the subscripts represent:

A = I for instantaneous injection
= C for continuous injection

B = R for ‘resident’ concentration specification of input
= F for ‘flux’ concentration specification of input

C = R for ‘resident’ concentration measurement method
= F for ‘flux’ concentration measurement method

This gives 8 possibilities in total:
$C_{IRR,}$ $C_{IRF,}$ $C_{IFR,}$ $C_{IFF,}$ $C_{CRR,}$ $C_{CRF,}$ $C_{CFR,}$ C_{CFF}

Gershon and Nir (1969) provide analytical solutions for one-dimensional convection dispersion with a wide variety of boundary conditions.

For a borehole dilution test, the concentration falls off exponentially with time. So if tracer in a borehole to borehole test is injected suddenly into one well the source term is not a pulse but an exponentially decaying concentration input. In a similar manner, if detection is by sampling the second well in which the water is well mixed, the average concentration in the borehole is a time-average of the concentration arriving at the well.

B.5 Transfer function modelling

As indicated earlier, it is possible to analyse tracer tests to produce characteristic parameters without employing a model based on processes such as sorption and diffusion. While such an approach has serious disadvantages it is relatively easy to apply, it does give some insight and is not subject to errors due to incorrect conceptualisation of the system.

An ideal tracer test is a concept that needs discussion. A mass of tracer, M, is instantaneously injected into a system at time zero and observed at some point (possibly the injection point) from that time onward to obtain a continuous concentration curve. Mathematically, the injection will be described by a 'delta-function', $M\,\delta(t)$, and the observed concentration by a general function, C(t).

Although the full data set of concentration values might be retained to characterise C(t), if this function is not too complex then it might reasonably be represented by certain features such as: the time when the concentration was first detected, the time when the concentration reached a maximum (and the concentration at that time) and the time when the concentration became negligible. A mathematical approach would be to represent C(t) by its statistical moments over time:

$$C_N = \frac{\int_0^\infty t^N\, C(\tau)\, d\tau}{\int_0^\infty C(\tau)\, d\tau} \qquad \text{(B.1)}$$

In practice the concentration measurements are discrete and this integral would need to be replaced by a summation. The accurate evaluation of the moments is not, however, possible unless most of the tracer is recovered.

The more mathematical reader will be aware that in the modern literature most analytical tracer-test models are developed by use of Laplace transforms. It is readily shown that the Nth moment of the concentration function, C(t), can be derived from its Laplace transform, $\bar{c}(p)$, through

$$C_N = (-1)^N \left. \frac{d^N \bar{c}(p)}{d\,p^N} \right|_{p=0} \qquad \text{(B.2)}$$

where p is the transform variable. Although of no direct practical value, Equation B.2 can be used to readily relate analytical models to moment estimates.

A more natural approach than the use of moments is to take a statistical viewpoint and obtain statistics of the concentration distribution. However, this is equivalent to evaluation of the moments as will be seen below. The average transit time from injection to detection is

$$\bar{t} = \frac{C_1}{C_0} = \frac{\int_0^\infty t\, C(T)\, dt}{\int_0^\infty C(T)\, dt} \qquad \text{(B.3)}$$

and the variance is given by:

$$\sigma_t^2 = \frac{C_2}{C_0} - \frac{C_1^2}{C_0^2} = \frac{\int_0^\infty \left(t - \bar{t}\right)^2 C(t)\, dt}{\int_0^\infty C(t)\, dt} \tag{B.4}$$

It is instructive to consider some (simple) specific concentration distributions (Table B.1).

Case 1

Peaks of concentration in the unsaturated zone of aquifers (e.g. tritium peaks) have often been observed to move downwards with little dispersion over a period of many years. The piston-flow model can under those conditions be adopted although it is obviously an approximation.

Case 2

Any system with strong mixing (e.g. some lakes) can reasonably be considered as a well mixed system and will behave according to the exponentially decreasing concentration as a result of flushing by inflowing water. Some data exist which indicate that the unsaturated zone of fractured karst systems conform to this case (Atkinson, pers. comm.).

Case 3

Solving the convection-dispersion equation in an infinite medium, the concentration at distance x from the injection point after time t with velocity v is given by:

$$\frac{M}{2\sqrt{\pi D t^3}} \exp\left[-(x - vt)^2 / (4Dt)\right] \tag{B.5}$$

where D is the longitudinal dispersion coefficient. Comparing this equation with that given for Case 3 in Table B.1, in terms of transit time statistics for a given x, gives

$$\begin{aligned} v &= \frac{x}{\mu} \\ D &= \frac{\sigma^2 x^2}{2\mu^3} \end{aligned} \tag{B.6}$$

In principle, the last equation could be used to define a dispersion coefficient for any breakthrough curve in terms of its moments.

See Jury and Roth (1990, pgs 34-35) for further discussion.

Case 4

A skewed distribution with a long tail is widely observed. Individual examples can sometimes be approximated by a lognormal distribution, although this lacks a theoretical basis. Gamma distributions sometimes fit data equally well but are equally unfounded in theory.

Table B.1 Some basic transfer-function models that are used with tracer tests.

Case	C(t)	$\bar{t}$	σ_t^2	System type
1	$\delta(t-\tau)$	τ	0	‘Piston flow’ or ‘plug flow’. No dispersion. Travel time τ .
2	$\lambda \exp(-\lambda t)$	$1/\lambda$	$1/\lambda^2$	Uniformly mixed system, steady flushing (e.g. borehole dilution)
3	$\frac{1}{\sigma\sqrt{2\pi t^3/\mu^3}}\exp\left[-(t-\mu)^2/(2\sigma^2 t/\mu)\right]$	μ	σ^2	Advection and Fickian dispersion.
4	$\frac{1}{t\sqrt{2\pi\sigma^2}}\exp\left[-(\ln t-\mu)^2/(2\sigma^2)\right]$	$\exp(\mu-\sigma^2/2)$	$\exp(2\mu-2\sigma^2)$ $-\exp(2\mu+\sigma^2)$	Lognormal distribution

B.6 Spectral analysis of tracer tests

In essence, a spectral method replaces time-dependent functions by their frequency-dependent equivalent functions derived by Fourier analysis. In practice numerical procedures such as the fast Fourier transform are employed.

A spectral method was developed for the advection-dispersion equation by Duffy and Gelhar (1985): they considered a dipole flow field and radioactive decay. That method was applied by Duffy and Al-Hassan (1988) to tracer experiments over distances up to 6 m. They found that the spectral method gave more reliable values for dispersion parameters. Marschall and Schafer (1984) similarly found the spectral method superior to both moment-analysis and least-squares methods of parameter estimation.

Datta-Gupta et al (1995) introduce type-curves via a spectral method which can be used to obtain a measure of heterogeneity in the system.

B.7 General input

The cases considered above are restricted to an instantaneous input of tracer, which is difficult to approximate in practice. It is therefore necessary to consider a time dependent input of tracer concentration, $c_{in}(t)$. This input can be considered as a sequence of pulse inputs - each of which results in a concentration $C(t)$ - and the combined concentrations obtained by adding these gives the generalised concentration:

$$c(t) = \frac{\int_0^\infty c_{in}(t-\tau)\, C(\tau)\, d\tau}{\int_0^\infty C(\tau)\, d\tau} \qquad \text{(B.7)}$$

Strictly, this equation only applies when the transport equations are linear or, in physical terms, when the behaviour of tracer particles do not affect one another. Sorption, for example, can cause non-linear behaviour as sorbed particles prevent other particles being sorbed to the same sites.

B.8 The multi-dispersions-model (MDM)

Maloszewski et al (1992) developed the MDM which is a simple extension of the advection dispersion model from a single pathway to N pathways. For each pathway the concentration, resulting from an instantaneous injection, is given by

$$C_i(t) = \frac{M_i}{Q_i} \frac{1}{t_{0i}\sqrt{4\pi P_i\,(t/t_{0i})^3}} \exp\left[-\frac{(1-t/t_{0i})}{4P_i\; t/t_{0i}}\right] \qquad \text{(B.8)}$$

and the total concentration is simply

$$C(t) = \sum_{i=1}^{N} C_i(t) \qquad \text{(B.9)}$$

i = index for flow path
C = tracer concentration
M = tracer mass
Q = discharge
t_0 = mean transit time
P = dispersion parameter (= dispersivity/distance)

Each pathway is characterised by three parameters, Q, t_0, and P. This is effectively the same as a multi-channel model with the addition of (Fickian) dispersion.

Generalisation to more complex models for each pathway is obvious but the danger is that the number of parameters would become too large and the result of any model calibration would not be meaningful.

B.9 Point dilution method

One model that is very specific to tracer testing is the solution for point dilution in a borehole. The tracer is injected (uniformly, if possible) into a borehole and the concentration within the borehole measured. Water flowing into the open section of the borehole will dilute the water within the borehole giving a falling tracer concentration.

A variety of equations have appeared in the literature for determining aquifer flow velocities from borehole dilution tests. These equations are not the same and some are incorrect (e.g., Lewis et al 1966 eqn. 2.3.4, Davis et al 1985 pg36). Therefore a derivation of a correct form of the appropriate formula is given here.

The following assumptions are made:-

- The concentration within the borehole remains uniform and equal to the concentration leaving the borehole.
- The concentration at time zero is instantaneously raised to c_i.
- Water enters the borehole from an aquifer thickness equal to the screened length of the borehole (i.e. there is no vertical flow in the aquifer).
- Water upstream of the borehole is at a uniform background concentration of c_b.
- The flow is steady-state.

It follows from these assumptions that the change of tracer mass in the borehole in time Δt will equal the difference between the mass fluxes into and out of the borehole:

$$\pi R^2 L_{sat} \Delta c = q L_{scrn} \alpha D (c_b - c) \Delta t \tag{B.10}$$

where:

R	is the borehole radius
L_{sat}	is the saturated depth of the borehole
Δc	is the change in borehole concentration
q	is the Darcy velocity in the aquifer
L_{scrn}	is the open length of the borehole (often the screened length)
a	is the ratio of the width of the aquifer contributing flow to the borehole to the borehole diameter (see Figure B.1)
D	is the borehole diameter ($2R$)
c_b	is the background aquifer concentration of the tracer (often zero)

The above equation can be integrated from time zero (borehole concentration c_i) to any given time t (borehole concentration $c(t)$):

$$\pi R^2 L_{sat} \int_{c_i}^{c} \frac{dc'}{c_b - c'} = q L_{scrn} \alpha D \int_{0}^{t} dt' \tag{B.11}$$

Performing the integrals gives:

$$\pi R^2 L_{sat} \ln\left(\frac{c_b - c}{c_b - c_i}\right) = q L_{scrn} \alpha D t \tag{B.12}$$

This can be rearranged to give the Darcy velocity, q, and thence the true velocity, v:

$$v = \frac{q}{n_e} = \frac{\pi R L_{sat}}{2 n_e L_{scrn} \alpha t} \ln\left(\frac{c - c_b}{c_i - c_b}\right) \qquad \text{(B.13)}$$

where n_e is the kinematic porosity and *D* has been replaced by *2R*.

For the purposes of data analysis, field data is often plotted on semi-logarithmic paper and so it is preferable to write this equation in the form:

$$\log\left(\frac{c - c_b}{c_i - c_b}\right) = At + B \qquad \text{(B.14)}$$

where the slope, *A*, of the plot of $\log[(c\text{-}c_b)/(c_i\text{-}c_b)]$ versus *t* (which can be determined graphically or otherwise) is given by:

$$A = \frac{2 n_e L_{scrn} \alpha v}{\ln(10) \pi R L_{sat}} \qquad \text{(B.15)}$$

This leads to the aquifer flow velocity in terms of *A*:

$$v = \frac{\ln(10) \pi R L_{sat} A}{2 n_e L_{scrn} \alpha} \approx \frac{3.6 R L_{sat} A}{n_e L_{scrn} \alpha} \qquad \text{(B.16)}$$

which is the required result.

The quantity α can have a value anywhere in the range 0 to 8 and depends on: the hydraulic characteristics of the aquifer, the gravel pack (if any) and the well screen (Klotz et al. 1972). Ignoring any head loss across the well screen, which will normally be negligible:

$$\alpha = \frac{4 \kappa \rho^2}{\kappa(\rho^2 + 1) + \rho^2 - 1} < 4 \qquad \text{(B.17)}$$

where:

k	is the ratio of gravel pack to aquifer hydraulic conductivity
r	is the ratio of gravel pack radius to well radius.

When there is no gravel pack α=2, which will suffice in many cases.

Therefore for a dilution test carried out in an open hole, where $L_{scrn} = L_{sat}$, when *a* is taken as 2, the true velocity can be calculated by plotting a graph of $(c\text{-}c_b)/c_i\text{-}c_b)$ on the log scale of semi-log paper against t on the linear scale. A straight line, of slope *A*, is drawn through the data and the velocity is calculated using the following simple equation:

$$v \approx \frac{1.8R}{n_e} A \qquad \text{(B.18)}$$

B.10 Radial test analysis

Hoopes and Harleman (1967) presented an approximate solution for radial advection with dispersion. The concentration *C(r,t)* at radial distance r at time t is given by:

$$\frac{C}{C_0} = \frac{1}{2}\mathrm{erfc}\left[\left(\frac{r^2}{2} - rvt\right)\left(\frac{4}{3}\alpha_L r^3 + \frac{D^*}{v} r^3\right)^{-1/2}\right] \qquad \text{(B.19)}$$

where the injection concentration is C_0 at $r=0$, v is velocity at radius r, α_L is the longitudinal dispersivity and D^* is the coefficient of molecular diffusion.

More precise analytical solutions were given by Moench and Ogata (1981) and Falade and Brigham (1989). Those solutions require computer evaluation while the above (approximate) solution can be readily evaluated using a spreadsheet, for example. See also Sauty (19??) for both analytical and numerical approaches, type curves and a wide discussion of the radial flow problem.

B.11 Double porosity media

B.11.1 *Introduction*

The major aquifers of the UK are all in porous fractured rock. Transport through them is largely dominated by advection in the fractures. When a tracer passes through the fractures it will tend to diffuse into the relatively stagnant pore water of the rock ‘matrix’. When a tracer test is carried out in such rocks it would be hoped that the results could be analysed to determine all the relevant transport parameters. Unfortunately that cannot be presumed to be the case for reasons outlined below.

The phenomenon we wish to concentrate on is that of molecular diffusion, and the times over which it has effect. The additional problem of scale dependence of dispersion parameters has been discussed in section 7.3 of this report.

A large number of parameters are used to characterise rock and many more are used when the rock is fractured. For example, geotechnical engineers are concerned with the load bearing capacity of rock which is related to the fracture pattern. For our purposes those parameters which relate to the water flow and solute transport are required. A significant problem can be that many fractures may take little water. Therefore simple statistics on fracture frequency, for example, only indicate the frequency of fractures active in flow and are unlikely to represent quantitative flow conditions. As a general principle, it is important to determine hydrogeological transport parameters empirically and directly.

In a series of papers, Barker (1982, 1985a, 1985b) developed a general model of flow and transport in double porosity media. It is therefore appropriate to consider the parameters used by the model.

The Block Geometry Function (BGF) model of Barker (1985a) introduces a parameter which represents the ratio of the matrix and fracture porosities. This is represented here by the symbol σ which equals the porosity of the matrix void volume per unit volume of rock matrix divided by the fracture void volume per unit volume of total space within the rock. So the total porosity (matrix plus fractures) is $1+\sigma$ times the fracture porosity. More precisely, sigma is the ratio of the matrix volume to fracture volume in a given total volume, times the ratio of D_E and D_A (diffusion coefficients, defined below) which is the ‘fictitious’ porosity.

A non-mathematical version of the following discussion is given in Section 7.5 and most readers should benefit from that brief overview.

B.11.2 *Diffusion times*

There is significant room for confusion over the meaning of the term *diffusion coefficient* as several related parameters are in use. Alternative symbols and forms of nomenclature are employed, and terms are often not clearly defined. Errors in the literature are therefore not infrequent; when in doubt it is best to have regard to the equations used to describe transport. Brief clarification is given here for the case of diffusion without surface diffusion, and when the concentration is low, so diffusion is independent of concentration.

If x is a principal direction of the diffusion tensor, Fick's first law can be expressed as

$$J = -D_T \frac{\partial c}{\partial x} \qquad \text{(B.20)}$$

or

$$J_m = -D_E \frac{\partial c}{\partial x} \qquad \text{(B.21)}$$

and Fick's second law takes the form

$$\frac{\partial c}{\partial t} = D_A \frac{\partial^2 c}{\partial x^2} \qquad \text{(B.22)}$$

where:

J = mass flux in the x direction in water (no rock matrix)
J_m = mass flux (per unit area of water and rock) in the x direction in saturated rock
c = mass per unit volume of water (not matrix and water)
t = time
D_T = tracer diffusion coefficient (d.c.) or free-water d.c.
D_E = effective d.c. or intrinsic d.c.
D_A = apparent d.c.

These three diffusion coefficients are related through:

$$D_E = \alpha D_A = \psi D_T \qquad \text{(B.23)}$$

where:

α = the 'rock capacity factor' or 'fictitious porosity' (total porosity times retardation coefficient)
R = the retardation coefficient
ψ = $\phi_D \delta / \tau^2$ 0, the diffusibility
ϕ_D = the through-diffusion porosity
δ = constrictivity
τ = tortuosity

Note that

$$D_E < D_A < D_T$$

Block sizes

The model of Barker (1985a) characterises the size of a block by its volume to surface area. This length is represented here by ℓ. Whatever the shapes of blocks, this parameter is meaningful; however, it is far from easy to measure.

Block diffusion time

The diffusion coefficients and block sizes do not appear separately in the BGF model but in combination as ℓ^2/D_A. This parameter is best regarded as a characteristic time for diffusion across a matrix block and will be represented by t_{cm}. More precisely, ℓ, is the root-mean-square distance of diffusion in time $\ell^2/2D_A$.

Example times for diffusion over given distances are given in Table B.2.

The values indicate that diffusion over a distance of 7 mm takes about one day. This implies that water in a fracture with aperture of about 1 mm (which would be a relatively large chalk fracture) will approach equilibrium with a volume of about five times as much water (14 mm times 30% porosity) in one day. It should therefore move roughly 80% of the way from its initial concentration to that of the matrix water in about one day.

Table B.2 Typical diffusion times for given distance (D_A=3×10^{-10} m^2/s)

Distance		Time	
0.1	mm	17	sec
1	mm	27	min
1	cm	46	hours
10	cm	193	days
1	m	53	years
2	m	211	years
5	m	1320	years

Fracture diffusion time

While the porosity ratio, block diffusion time and block shape fully describe the behaviour of a double porosity system, another parameter can be more characteristic of certain behaviour. This is the characteristic time for diffusive equilibrium between the fractures and the matrix: it is equal to the block characteristic time divided by the square of the porosity ratio: $t_{cf} = t_{cm}/\sigma^2$.

This parameter tends to be important when the interaction time between the fracture water and the matrix water are less than the time for diffusion across a matrix block. Under those conditions the fracture water concentration is determined mainly by the surface available for diffusion in relation to the fracture size. The block size and geometry become unimportant. The time t_{cf} can be thought of as the time for diffusion through a matrix volume equal to the fracture volume.

B.11.3 *Block shapes*

The Block Geometry Function (BGF) model has at its heart a characterisation of block shape based on the diffusion equation. The form of this is a function of a single variable for a given geometry. For simple geometries, such as the sphere, this function is quite simple. For any well defined geometry, even mixtures of blocks of different shapes and sizes, this function can be determined.

The size of the blocks does not come into this function but is separately introduced into the model by the parameter ℓ discussed above.

Empirical BGFs can in principal be defined but there is no record of this approach in the literature.

When the rock matrix material is capable of significant adsorption, it must be recognised that the diffusion process can make much more surface area available for that process than exists at the boundary of the mobile phase. For example, the internal surface area per cubic centimetre of chalk is of the order of one square metre: so, for a typical molecular diffusion coefficient (a little in excess) of 10^{-10} m^2/s, the area accessible to a diffusing solute after 1 day is equal to the surface area of the blocks multiplied by a factor of about 10 to 100. The fracture-surface adsorption can then often be ignored, or can be regarded as part of the internal matrix surface.

Mineral or organic deposits are quite often observed on the surfaces of fissures, and when present these must have a significant impact on the amount of adsorption taking place, both by providing adsorption sites and by acting as a barrier for diffusion into the matrix. Some models include a *fracture skin* to take some account of this phenomenon.

Molecular diffusion is usually considered to be of negligible importance compared to hydrodynamic dispersion (discussed below). However, it can be the dominant dispersive process when flow velocities become very small and for fractured porous media (Barker 1993).

B.11.4 *A simple double-porosity model*

It is instructive to consider the specific case of one-dimensional transport through a homogeneous double-porosity medium with no dispersion within the fracture system. The resulting solution takes a very simple form when expressed in Laplace transforms which readily reveals the parameter dependency of the problem. (The reader requires no knowledge of the theory of Laplace transforms.)

For an instantaneous pulse concentration at the origin the solution takes the form:

$$\bar{c}(x,p) = c_0 \exp(-\mu t_f) \tag{B.24}$$

where t_f is the travel time in the fractures (distance divided by average velocity), c_0 is the time-integrated concentration, and

$$\mu = p\left[1 + \sigma B\left(\sqrt{pt_{cm}}\right)\right] \tag{B.25}$$

The quantity t_{cm} is the characteristic time for diffusion across a matrix block introduced above.

The function *B* (which Barker (1985a) termed the block-geometry function) also implicitly contains a set of parameters: that set can be infinitely large. (For example, for matrix material in the form of planar slabs, B(x)=tanh(x)/x) and ℓ is half the block thickness.)

The above solution suggests that a tracer test with a diffusing tracer will reveal the parameters σ, t_{cm} those relating to the geometry and the average travel time in the fractures, t_f.. However, the information revealed depends on the duration of the tracer test.

Suppose a test is carried out very fast so that no significant diffusion into the matrix occurs. Clearly, the test will reveal nothing about the shapes or sizes of the matrix blocks.

If the test is carried out a little slower there will be some diffusive exchange but if the diffusive penetration into the matrix is small compared to the block size only the surface area in contact with he fractures and the diffusion coefficients will take effect. The same effect arises if the fracture volume is so large that the proportion of mass exchanged with the matrix is negligible in relation to the total volume. Under these circumstances the function B(x) tends to 1/x and the parameters σ and t_{cm} become combined in the combination t_{cm}/σ^2 which is exactly the quantity t_{cf} earlier referred to as the fracture diffusion time.

Now suppose the test is very long. This might better represent a ‘natural’ tracer test such as the migration of a pollution plume. Under such circumstance, it may be that there is locally little variation of tracer concentration through any matrix block. A similar circumstance arises if the matrix blocks are very small so diffusive exchange is fast. This is rarely the case except in near-surface weathered rock. Under these circumstances the function B(x) tends to 1 and the solution given earlier contains the group ($1+\sigma$) which can variously be thought of as a total porosity or a retardation term.

Clearly, different parameters are revealed by tracer tests conducted over various time scales relative to the times for diffusion over distances of the order of the fracture aperture and the fracture separation. The parameters required to represent transport under conditions of practical interest are for the same reasons likely to differ from those obtained from tracer testing. Significant care is required in designing appropriate tests in double-porosity aquifers.

It is worth considering the use of various tracers. A particulate tracer will tend to stay in the fractures and not be lost by diffusion. Even different chemical tracers may have quite different diffusion coefficients and their combined use can provide significantly more information than a single tracer. (It is worth remembering that the matrix porosity the tracer diffusion coefficients of tracers are likely to be known.)

B.12 Review of software for tracer test analysis:

The following review is of packages that are readily obtained. There are many further packages available; for example, which may be obtained directly from their authors.

CATTI: Computer Aided Tracer Test Interpretation.

Summary of Model

This program is specifically designed for tracer test interpretation. It computes breakthrough curves of tracers in observation wells for known aquifer parameters or aquifer parameters from measured breakthrough curves.

There are several models available to the user. These can be either analytical or numerical and cover 1-D and 2-D uniform flow, converging radial flow and except in the 2-D case can simulate 2 interactive layers (dual porosity). Each model assumes a confined, homogeneous aquifer of fixed thickness. In general the tracer input is assumed to be instantaneous although there is a 2-D uniform flow with constant injection option as a first approach to modelling pollution plumes.

By using tracer test data the program allows one to manually calculate the effective aquifer properties by curve fitting. One can also calculate the direction of flow using the results of two or more observation wells.

The program is menu driven and has a full graphical output facility.

Model Geometry:	One-dimensional, two-dimensional rectangular or radial geometries are supported.
Aquifer Type:	In general this is a homogeneous, confined aquifer. However the one-dimensional and radial options allow for two interacting layers to be modelled for simulating dual-porosity calculations.
Tracer Source Type:	Instantaneous source only except for the two-dimensional case where a continuous source can be modelled. A single injection well is used for each run.
Transport/Tracer information:	Transport mechanisms are advective and dispersive.

Program Information

The program is written in Microsoft QuickBasic 4.0. It requires DOS 3.1 or higher and 640Kb RAM with a math coprocessor. The program is menu driven and has graphical output facilities.

Source Code Available? Yes.
Input Method: The data is input interactively by form filling whilst the program is active.
Output Method: The results are output graphically on the screen, or stored as HPGL-graphics files. These files can then, for example be imported into Microsoft Word.
Example Problems: There are example sessions detailed in the documentation. Sample tracer test files exist to allow one to practice both calculation of breakthrough curves and estimation of parameters.

Supporting Documentation

The program information is good. Each mathematical model is described separately and the relevant references given. The sample sessions are complete and quite useful.

Program Review

This program is pleasant and easy to use and the documentation complete. As a first analysis tool it is good. The obvious drawback is that for more complex situations it will be no more than a coarse approximation to the real situation. This being the nature of analytical solutions does not detract from the software.

CXTFIT: Determining Transport Parameters From Laboratory and Field Tracer Experiments.

Summary of Model

CXTFIT is used to fit experimental or field data to simulated (analytical) breakthrough curves or resident solute concentrations.

The models employed are one dimensional, can be stochastic or deterministic and model advection, hydrodynamic dispersion/molecular diffusion, decay and adsorption. Adsorption is paid particular attention with either linear equilibrium or two site equilibrium/kinetic models employed. A distinction is made between flux averaged and volume averaged concentrations. This allows one to choose of the most appropriate model for modelling specific field observations.

The option exists to either simulate a set of observations, or to fit a choice of model to existing data in the least squares sense. Therefore the program allows determination of user selected aquifer parameters. Furthermore one can place constraints on the parameters to bias the results toward expected values.

A pre/post processor is available to make the package easier to use.
Model Geometry: The models are one dimensional linear.
Aquifer Type
The stochastic model options allow the determination of confidence limits in the results. Therefore implications can be drawn on the level of non-homogeneity in the aquifer. The different adsorption options can be used to infer single or multiple constituents in the solid phase.
Tracer Source Type
This is limited to an instantaneous point source.
Transport/Tracer information
Advection, equilibrium or kinetic adsorption, decay/production and diffusion are the transport effects modelled. The tracer can undergo radioactive decay, can react with the aquifer constituents or can be conservative.

Program Information

The program is written in PASCAL for the DOS environment. It requires 640Kb RAM, 0.5 Mb hard disk space, Dos 3.1 or higher and CGA/EGA graphics.
Source Code Available?
Yes.
Input Method
By user edited input file only, although the DOS based pre-processor facilitates this.
Output Method
By output file and by graphical means via the post processor.
Example Problems
Some examples are given in the text and a single example input/output file is provided.

Supporting Documentation

The main documentation provided is in the form of booklet which deals in detail with the model and it’s applications. It is quite mathematical in approach and is therefore quite hard going at times. It is however well written.

Detailed explanations of the input and output files are given and several example applications are analysed.

CYLTRAN: Finite Element Programs For Flow And Mass Transport Under Cylindrically Symmetric Conditions.

Summary of Model

The model is numerical and uses the finite element approach to calculate the flow field, flux field and concentration of a tracer in the region surrounding an injection well. Radial symmetry is assumed although layered permeability can be modelled with varying horizontal to vertical permeability ratio between layers. A single tracer can be modelled for advective, adsorptive and dispersive effects. Graphical output is available in the form of pressure heads, flux fields, concentration plumes and breakthrough curves for single borehole tracer tests.

Model Geometry

Cylindrical.

Aquifer Type

Layered aquifer with each layer having individual properties specified by the user.

Tracer Source Type

Can be specified by the user. The well can be fully open or can have closed sections as required. The concentration can be varied both in time and along each well section.

Transport/Tracer Information

A conservative tracer is modelled. Advective, adsorptive and dispersive effects are included.

Program Information

CYLTRAN consists of three programs to be run sequentially. They calculate the flow, flux and solute transport.

Source Code Available?

Input Method

Data input is by three input files, one for each sub-program.

Output Method

The data is initially in the form of output files although specific graphics programs exist for their presentation.

Example Problems

Two example problems are given in the documentation.

Supporting Documentation

The documentation is well written and clearly explains the model and some of it's applications. There is a detailed derivation of the model used. The input files are explained clearly.

Program Review

This program seems to provide a good method of simulating tracer tests in layered aquifer systems. It is more realistic than the other models discussed but the documentation describes the model and it's use very well. It has been specifically used for interpretation of single borehole test in mixed sediments.

It does not allow for direct computation of aquifer characteristics but can be used for more complex analyses and tracer test interpretations.

PLUME2D: Two-dimensional Analytical Solution for Transport of a Non-conservative Tracer in Ground Water.

Summary of Model

The PLUME2D program calculates an analytical, closed form solution of the non-conservative solute transport equation. Tracer releases can be instantaneous or continuous and the superposition of individual source solutions allows multiple sources to be analysed simultaneously. Solutions of this form are necessarily based on simple situations, in this case a homogeneous confined aquifer with uniform flow conditions. The x-axis is defined as parallel to the direction of flow which is assumed horizontal. Since the aquifer thickness is considered constant, the model is two-dimensional. Up to 25 fully penetrating sources are allowed, the fact they are non-interacting limits the accuracy of the solution somewhat but the model was designed as a tool for verifying more complex numerical solutions and not as a complete analysis tool.

Model Geometry

Two-dimensional rectangular grid.

Aquifer Type

Homogeneous, confined aquifer.

Tracer Source Type

Continuous or instantaneous source. Up to 25 fully penetrating injection wells.

Transport/Tracer information

Transport mechanisms are advection and dispersion. Adsorption can be handled via a retardation coefficient. Radioactive decay is possible.

Program Information

The program is written in Microsoft QuickBasic 4.5. It requires DOS 3.0 or higher and 640Kb RAM. There is no graphical input/output.

Source Code Available?

Yes.

Input Method

The data are input interactively and a summary input file is automatically created. Because of the simplicity of the model this process does not take long. The basic groups of input data are the (homogeneous) aquifer/flow properties, the well data (for each well) and the (rectangular) grid data.

Output Method

The output file contains data in the form of gridded x-y concentration values at a fixed time. The time is specified on input so for a breakthrough curve to be calculated the program would either have to be modified or a number of runs performed.

Example Problems

There are four sample problems given in the form of input and output files. These allow one to check the results of self-compiled versions of the program.

Supporting Documentation

The program information is adequate. The mathematical model is described in some detail and the relevant references given. The example input and output data is also given.

Program Review

This model is simple. This means that the results would only be useful at an early stage of the project or at the development stage or for the verification of other models.

The output does not lend itself ideally to tracer test work as it stands. This could be improved by changing the code. However another package to be reviewed ‘CATTI’ contains the same analytical solution as ‘PLUME2D’ but is designed as a tool for analysing tracer tests, is more general and has a graphical output facility.

SUTRA: Saturated-Unsaturated TRAnsport.

Summary of Model

This software allows one to study fluid flow and transport of solute or energy in the saturated and unsaturated zones. It uses a 2-D hybrid finite difference and integrated finite difference method to approximate the interdependent processes.

The solute transport models advection, equilibrium adsorption, production and decay and dispersion. The dispersion model can include velocity dependency.

A multiple sources of both fluid and energy/solute are permitted. They are separated into pressure specified and concentration specified. These can have time dependent values.

I order to generalise and be robust and accurate in the calculations the code does not concentrate on efficiency. Indeed for unsaturated flow fine gridding is needed since specialist non-linear methods have not been implemented. This make the code less efficient. As far as the authors are concerned "The unsaturated flow capability is thus provided as a convenience to the user for occasional analysis rather than as the primary application of this tool".

Although the numerical implementation is 2-D the aquifer thickness can vary from point to point, thus introducing an element of the 3-D model.

The standard input/output method is by ASCII files and printer plots although it is presently being developed to be used within the ARGUS ONE Windows pre/post-processing package.

Model Geometry

One or two dimensional with varying aquifer thickness. 1-D Radial geometry can be accommodated.

Aquifer Type

Anisotropic, unconfined and possibly unsaturated.

Tracer Source Type

Multiple sources are possible. These can be split into grid locations which have pressure specified as a function of time, flux specified or concentration/temperature specified. In the former two cases the incoming fluid can have time dependent concentrations or temperatures.

Transport/Tracer information

For solute advection, equilibrium adsorption, production and decay and dispersion can be modelled. The dispersion model can include velocity dependency. The production/decay mechanisms can be radioactivity, biological, or chemical.

Program Information

The code is written in FORTRAN 77. It is described as highly generalised and modular, allowing easy access for modifications.

Source Code Available?

Yes.

Input Method

With basic program by ASCII file only. A general (programmable) pre/post-processor which works with MODFLOW and SUTRA (amongst other codes) is available from ARGUS Interware Inc..

Output Method

Again by ASCII file. There are user definable options for output format within these files. The Windows program mentioned above ARGUS ONE can be used to view results.

Example Problems

Several example problems are given in the documentation. A general guide to the input procedure is described.

Supporting Documentation

The documentation provided covers the model in considerable detail. There is a complete discussion of the finite difference method in general, and the analysis SUTRA employs specifically.

Seven simulation examples are given although the input file to only one of these is listed.

A description of the code is also given. There is emphasis placed on the fact that the code is designed to be easily changed as required.

Program Review

Although the program is not specifically designed for tracer test work it can certainly be used to calculate breakthrough curves due to solute transport. It's main advantage is that it allows for simple simulation of transport through the unsaturated zone.
It is a model which allows more complexities than the analytical examples but not as specialised as CYLTRAN, and not as complex as SWIFT 486. It is a good general purpose numerical code.

The fact it can be used within the ARGUS environment in Windows makes it more pleasant to use. It can however be used effectively in DOS or any other platform with ASCII files as input/output.

The documentation is considerably detailed, especially in it's description of the finite difference models.

Although one cannot use this as a tracer test analysis tool on it's own, it is a good general numerical simulator which can be applied to tracer tests.

SWIFT 486:The Sandia Waste-Isolation Flow And Transport Model For Fractured Media.

Summary of Model

SWIFT 486 is a coupled fluid flow, heat transport, brine migration and radionuclide transport model. It is a numerical model which uses heterogeneous, fractured and dual porosity aquifer types to analyse a large number of problems including salt-water intrusion, nuclear waste isolation in various geological formations, heat storage in aquifers as well as tracer test analysis.

Observation wells may be specified at any location and the breakthrough curves calculated for a number of source types including multiple sources.

Although designed to simulate complex situations ,one can use SWIFT to analyse the effects of dual porosity on tracer tests in fractured aquifers for relatively simple cases also. The model does not allow for parameter estimation but is deterministic and can be used to verify results or estimate parameters by graphical methods.

One can choose whether to solve the whole heat/brine/flow model in transient mode or choose a number of other options, e.g. ignoring heat or choosing steady state options.
The output can be used with the contour plotting package SURFER.

Model Geometry
Either Cartesian, up to three dimensional, or cylindrical.
Aquifer Type
With Cartesian Geometry the aquifer can be fully heterogeneous and the relevant data entered on a regional basis. For the cylindrical geometry the heterogeneities may exist in the vertical direction only. The model specifically deals with fractured aquifers and allows for dual porosity effects.
Tracer Source Type
The model allows for multiple tracer sources. They may be wells, so that the concentration may be any function of time, or they may be radionuclide sources, e.g. dumped waste with specific locations within the matrix.
Transport/Tracer Information
Since SWIFT 486 is a fully coupled fluid, heat, radionuclide and brine transport model then as well as advection, diffusion/dispersion along fractures and within the matrix, there is diffusion into the matrix and convective effects modelled. Furthermore the brine transport model includes salt dissolution.

The radionuclide model is also complex. The initial ‘parent’ source is given and the generation of new species calculated alongside decay. Waste leach effects are analysed.

Program Information

The program is written in FORTRAN. It requires the Salford compiler and is run on an IBM PC within the DOS environment. The amount of RAM/diskspace required depends on the size of problem one is analysing. The code can be changed to accommodate particular systems.
Source Code Available?
Yes.
Input Method
There is no pre-processor. This means that for each problem a data input file must be edited by the user. For large problems this can be a time consuming task. The documentation is quite helpful and fully describes each parameter.
Output Method
SWIFT 486 comes with a post processor called UNSWIFT. This allows the output files to be converted into a form for use with the SURFER package.

The form of the output files themselves can be specified using the input file.

Example Problems

A large number of example problems come with the package. These are automatically run on installation. Each problem is discussed in the documentation.

The problems are diverse and make full use of the facilities available within the package.

Supporting Documentation

The amount of documentation is substantial; There are self teaching manuals to accompany the example problems, theory and implementation manuals that discuss the model and it's uses, and a verification and field comparison manual. Furthermore there is a very useful data input guide that goes through the many input parameters and explains the input procedure. It also explains the unswift post-processing data input.

Program Review

The SWIFT 486 model is a complex one and includes many features which the simpler packages do not. For example fractures, dual porosity, radionuclide chains as well as decay, convection and saline/fresh water interactions. It's main drawback is the non existence of a pre-processor. This makes learning how to use it properly more time consuming. Nonetheless when learned it can provide a tool for modelling complex tracer test situations in a quite realistic manner. The data output method is not ideal but does allow for relatively easy graphical realisation.

The documentation is very good and quite comprehensive. A large number of very varied example problems means that these can be used as a basis for both learning the model and developing one's own problems.

WELL: Analysis of Two Well Tracer Tests with a Pulse Input.

Summary of Model

WELL is designed specifically for analysis of tracer tests in two well flow systems. It uses the theory of longitudinal dispersion along streamlines in non uniform flow to analyse the movement of a conservative solute introduced into the recharge well. Transverse dispersion is neglected.

The steady state flow regime is determined by either making the assumption that the flow rates at each well is equal, or by a complex graphical technique using a "fudge factor" to simulate the real situation. A curve matching technique is used to determine the porosity and dispersivity.

No boundary conditions are specified, presumably the graphical technique would be used to include any such effects in the model.

<u>Model Geometry</u>

Not specified.

<u>Aquifer Type</u>

Not detailed in the documentation. Homogeneity assumed because of the determination of a single porosity and dispersivity.

<u>Tracer Source Type</u>

Pulse input at recharge well.

<u>Transport/Tracer Information</u>

Conservative tracer. Transport by advection and dispersion along streamlines. Transverse dispersion is neglected.

Program Information

The program is written in ANSI FORTRAN 77 for the MicroSoft FORTRAN compiler Version 5.0. The hardware and software requirements are IBM PC with 640Kb RAM, DOS 3.0, math processor.

<u>Source Code Available?</u>

Yes

<u>Input Method</u>

Data files used and data for the flow regime and output required are given. There are options chosen for the type of model assumed.

<u>Output Method</u>

The output is in the form of an ASCII file of the breakthrough at the abstraction well. To analyse for dispersivity and porosity a curve matching technique is used.

<u>Example Problems</u>

Example input and output files are given. The method used to calculate the flow parameters is not detailed very well and the technique itself seems confusing.

Supporting Documentation

The documentation for this program is not clear and does not seek to explain the software, the model's assumptions or the methodology used to get results in a friendly manner.

Program Review

The program is not ideal because of the time needed to understand and apply the graphical technique for the flow conditions. Furthermore the results are not calculated but a curve matching method applied to approximate them. Presumably this requires a trial and error approach.

The documentation was found to be confusing and did not fully explain what the model's assumptions were.

If one assumes a equal flow regime for the two well system and therefore the simpler circular streamline approach, the technique may well provide adequate results. The software however is not easy to apply or use.

Software sources and costs

Software/ Version	Authors	Release Date	Supplier	Cost (1997)
Catti 2.0	J P Sauty W Kinzelbach	1988	IGWMC	$50
Cxtfit 1.0	J C Parker M Th van Genuchten	1985	IGWMC	$50
Cyltran	N Noy			
Plume2D 1.2	P K M van der Heijde	1986	IGWMC	$50
Sutra 2.0	C I Voss	1991	IGWMC	$200
Swift 486	D S Ward, A L Harrover, A H Vincent, B H Lester	1993	Geotrans	$800
Well 1.0	L W Gelhar	1992	IGWMC	$50

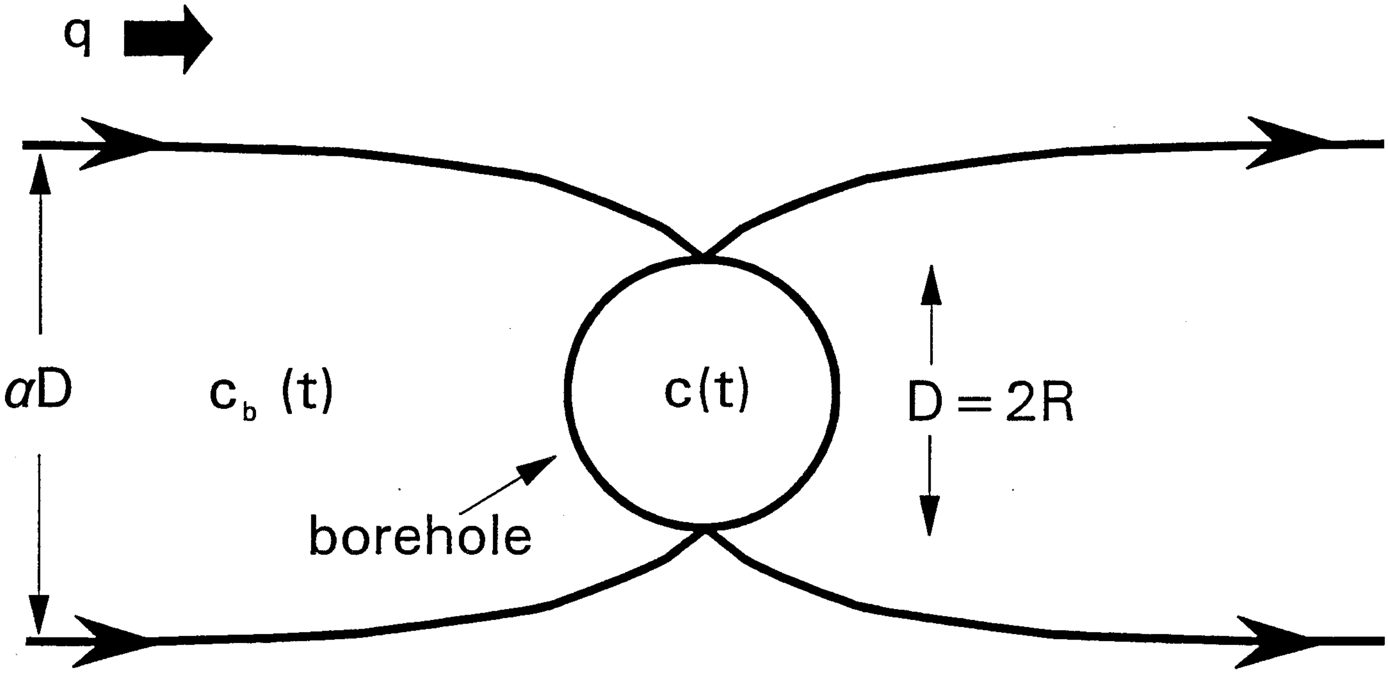


Figure B.1 Schematic showing width of aquifer contributing to the borehole

APPENDIX C

EXAMPLE OF A TRACER TEST DATA REPORT

British Geological Survey

Natural Environment Research Council

Fluid Processes Series
Technical Report WE/96/X

Banterwick Barn tracer test. Data report

compiled by:
R S Ward*

June 1996

contributors:
A T Williams†
L M Coleby†
L Brewerton†
J Talbot†
A Furey ^

• Fluid Processes Group, British Geological Survey

† Hydrogeology Group, British Geological Survey

^ Imperial College, University of London

British Geological Survey, Keyworth, Nottingham.

Preface

This data report presents a summary of a tracer test performed at Banterwick Barn, nr Hampstead Norris, Berkshire as part of the Chalk Aquifer Study (BGS National Groundwater Survey).The groundwater tracer studies, which forms part of the Chalk Aquifer Study, is jointly funded by BGS and the Environment Agency (Project no. BO4(94)01/587).

The aims of the tracer test at Banterwick Barn were to develop and apply testing methodologies under different flow conditions and at different scales. The experiment has provided invaluable experience of tracer testing in the chalk, enabled comparison of the different procedures employed, identification of likely problems and allowed refinement of test procedures.

The BGS would like to acknowledge the assistance and advice provided by the area and regional offices of the Environment Agency which enabled the reported test to proceed.

Banterwick Barn Tracer Test - Summary sheet

Geographical location:	Banterwick Barn, Nr Hampstead Norris, Berkshire
NGR	SU 5133 7757 (Abstraction well)
Boreholes	Abstraction well (equipped with pump). 762 mm diameter, 100m deep. Observation boreholes; BB-south (BB2) at 70 m (SU 5134 7750) (100 m deep) - used for tracer injection BB-west (BB1) at 284 m (SU 5105 7752) (100 m deep) - used for tracer injection BB-obs at 216 m (SU 5121 7775) (37 m deep).
Geology	Unconfined Chalk approx. sequence 0-40 m Upper Chalk 40-92 m Middle Chalk 92- ? m Lower Chalk
Weather	During the experimental period, weather conditions were variable but generally cool, moderately wet and windy.
Background samples	No samples were taken for background determination of tracer concentration. It was assumed that no tracer would be present and background concentrations would be low.
Rest Water Levels	SU 5133 7757 : 17.20 m bct (93.41 m aOD)
Pump	Electrically powered centrifugal. Intake at 50 m bct (60.61 m aOD). Rising main 350 mm diameter. Flow controlled by gate valve. Discharge during test maintained at 84 l/s (valve - one turn open). Valve must be set prior to switching pump on because it is very difficult (impossible ?) to adjust later.
Drawdown	Automatic monitoring of water levels in abstraction well and the two 100 m deep observation boreholes.
Local effects	No observed or monitored local effects resulting from pumping.
Hydraulic properties.	See analysis of drawdown data.
Tracer test method used	Radial converging test with injection borehole dilution monitoring and sampling of abstracted water
Tracers used	Amino G Acid, Fluorescein and Sodium Chloride
Quantities of tracer used	2 x 50 g Amino G Acid 1 x 100 g Fluorescein 2 x 750 g Sodium Chloride
Method of injection	(i). Single hose injection before initiation of pumping in two

	observation boreholes (ii). Repeat of (i) after extended period of pumping in closer of the two boreholes used in (i).
Time and date of injection	(i). 22-05-96, 10:51 to 11:02 (BB-south) 22-05-96, 12:40 to 12:59 (BB-west) (ii). 30-05-96, 14:22 to 14:32 (BB-south)
Sample collection	EC/T logging of injection boreholes for first injections (22-05-96). Sampling of discharge water at abstraction well during pumping manually and by automatic water sampler.
Sample storage	Glass bottles stored in the dark
Analysis times	Samples 1- 60 : 24-05-96 Samples 60 - 120 : 29-05-96 Samples 120 - 241: 04-06-96
Location of analysis	BGS, Keyworth
Analysis method	Fluorescence spectrophotometry
Results of analysis	see data sheets and breakthrough curves

Tracer Test Data

1. Tracer injection

Tracer was injected into two of the observation boreholes for the Banterwick Barn abstraction well (SU 5133 7757). The first injections were performed before the abstraction well had been switched on and whilst the aquifer was under natural flow (rest) conditions. 50 g of Amino G acid was injected in the observation borehole closest to the abstraction well BB-south/BH2 (70 m) and 100 g of fluorescein at the 100 m deep observation borehole, BB-west/BH1 at approximately 284 m.

After seven days of pumping, a repeat injection of 50 g of amino G acid was performed in the closest observation borehole, BB-south/BH2.

1. Injection borehole dilution

The dilution (migration) of the tracer from the injection borehole was monitored by adding salt (sodium chloride) to the injected fluorescent dye solution and measuring the electrical conductivity (EC) of the fluid within the injection borehole over time.

Salt was added to the dye tracers injected in the first phase of injection before pumping had commenced. Measurements of EC were made using a portable logging EC probe enabling the vertical distribution of tracer to be measured. Profiles of EC were obtained before and after injection.

The results of the initial concentration profiles are shown in Figure 1.1. Further profiles will be added later after processing.

Assuming a uniform injection was achieved, the results indicate that significant natural flow is occurring in the upper part of both injection boreholes with almost all of the tracer gone from the borehole between 40-50 m below casing top (bct) in BB-south/OBH2 and between 25-35 m bct in BB-west/OBH1. An additional outflow at 46 m in BB-west/OBH1 is also indicated. Flow towards the bottom of BB-west/OBH1 at around 97 m is also indicated.

2. Tracer breakthrough

After injection of the tracers and EC logging of the injection boreholes for the first phase of the test, the pump was switched on. The flow rate stabilised at approximately 84 l/s after 30 minutes form an initial flow rate of approximately 92 l/s.

Samples of the abstracted groundwater were sampled manually and by automatic water sampler. The samples were transferred to glass bottles and stored in the dark until analysis. Analysis was performed in the laboratory using a calibrated Hitachi F2000 Fluorescence Spectrophotometer.

The results of the analysis are shown in Table 2.1 and plotted in Figure 2.1. More detailed plots of the observed peaks are shown Figure 2.2 and 2.3

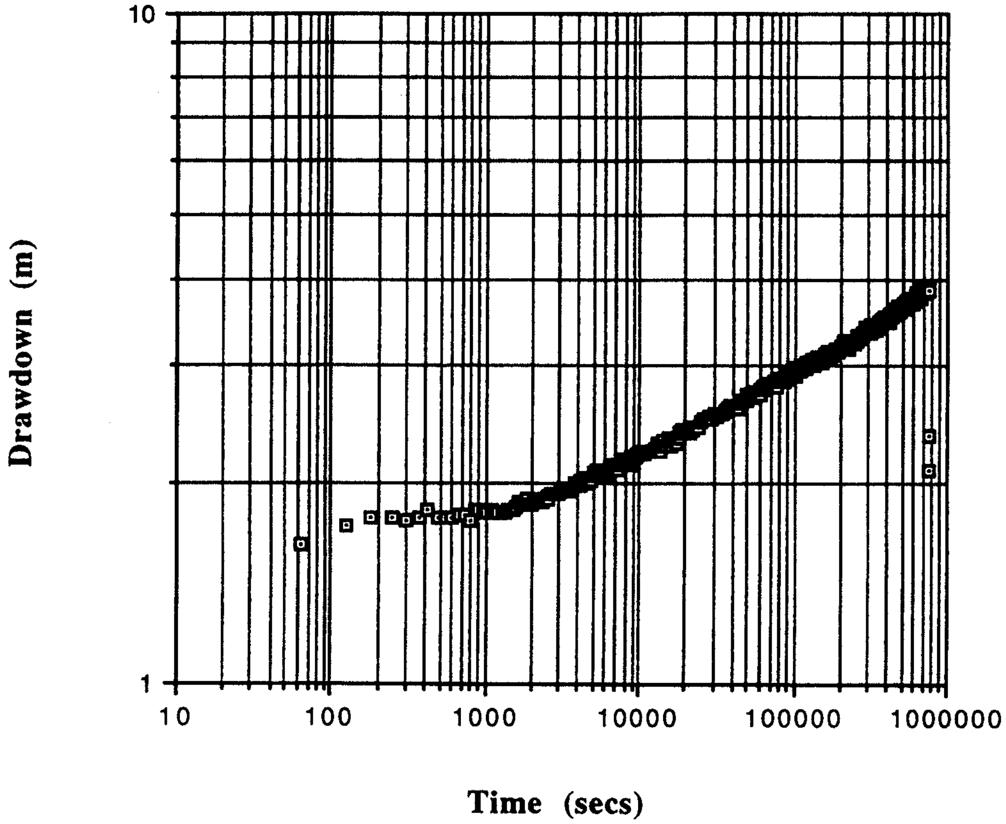
3. Hydraulic data

Water levels throughout the test were recorded in the abstraction well and the two observation boreholes used for the tracer injection. The drawdown data from the observation boreholes has been analysed to determine aquifer properties. The water level response to pumping and analysis are shown in Figures 3.1 and 3.2.

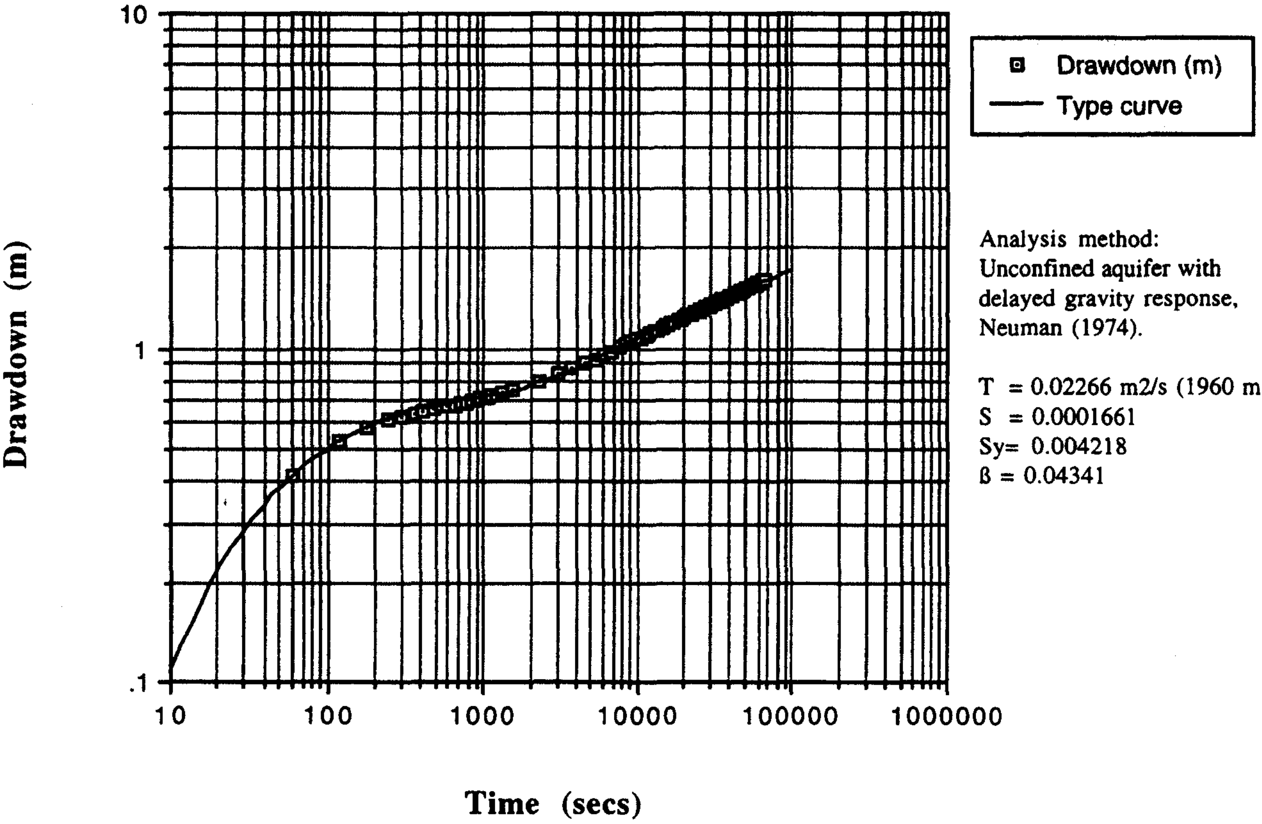
4. Cessation of test

The test was finished on 31-05-96 when the pump in the abstraction well was stopped. The site was cleared, tidied and returned to pre-test configuration.

Drawdown:
Banterwick Barn Abstraction Well (BB-abs)



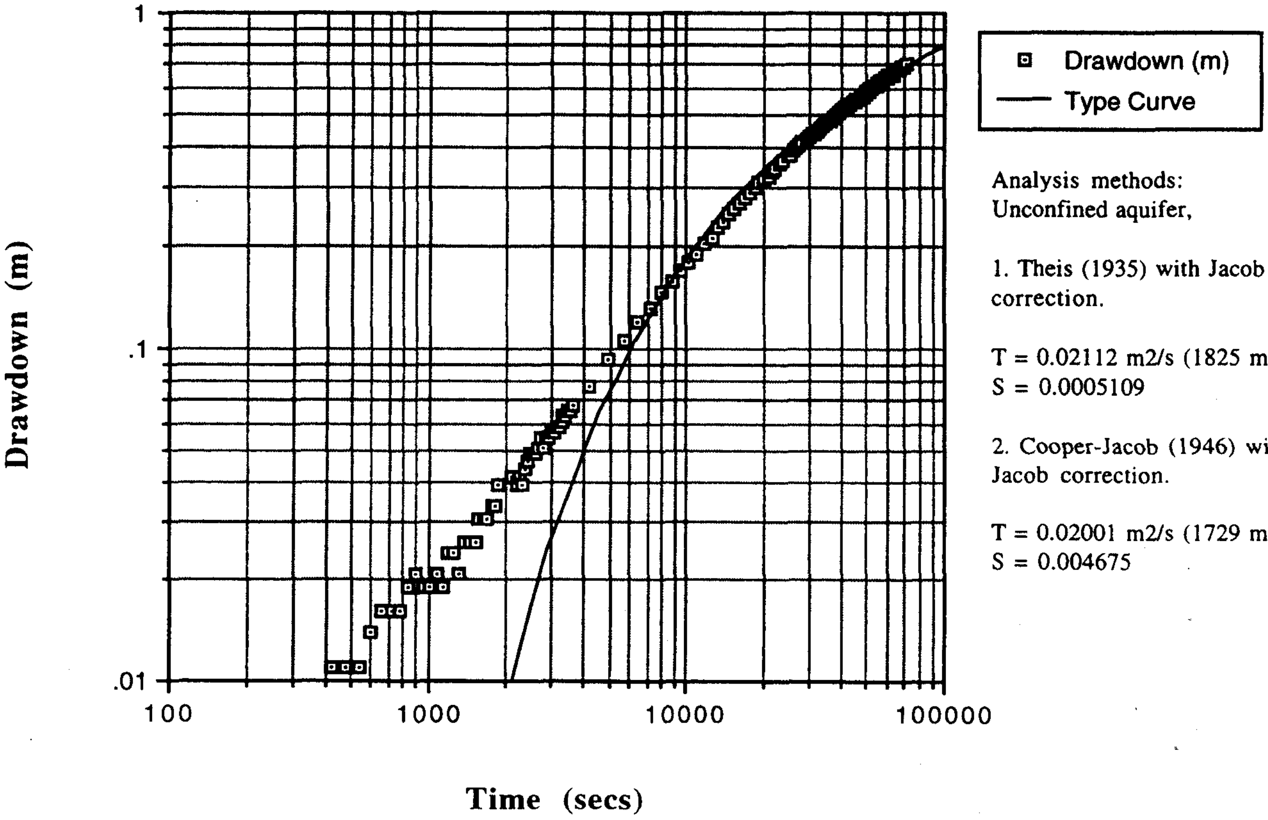
Analysis of drawdown: Banterwick Barn OBH 2 (BB-south).



Analysis method:
Unconfined aquifer with delayed gravity response, Neuman (1974).

T = 0.02266 m2/s (1960 m2/d)
S = 0.0001661
Sy= 0.004218
ß = 0.04341

Analysis of drawdown: Banterwick Barn OBH1 (BB-west).



Analysis methods:
Unconfined aquifer,

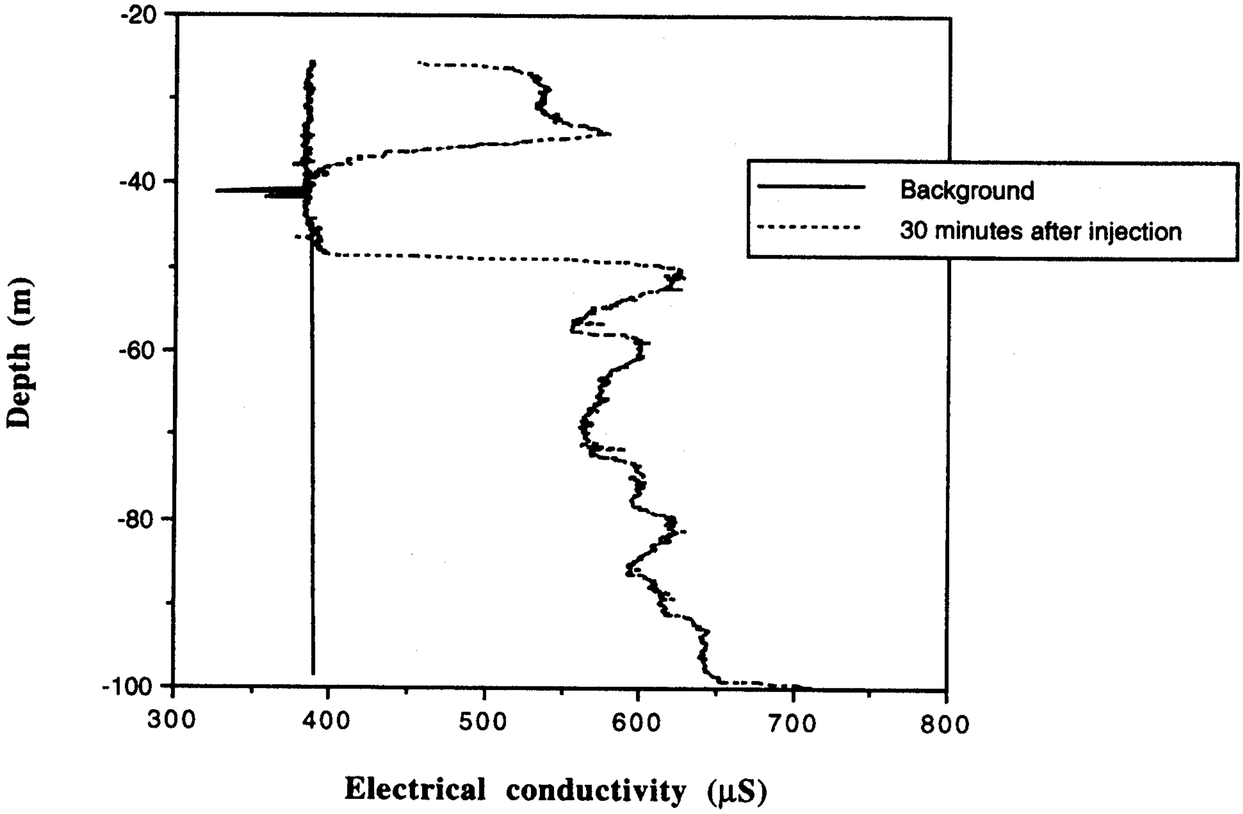
1. Theis (1935) with Jacob correction.

T = 0.02112 m2/s (1825 m2/d)
S = 0.0005109

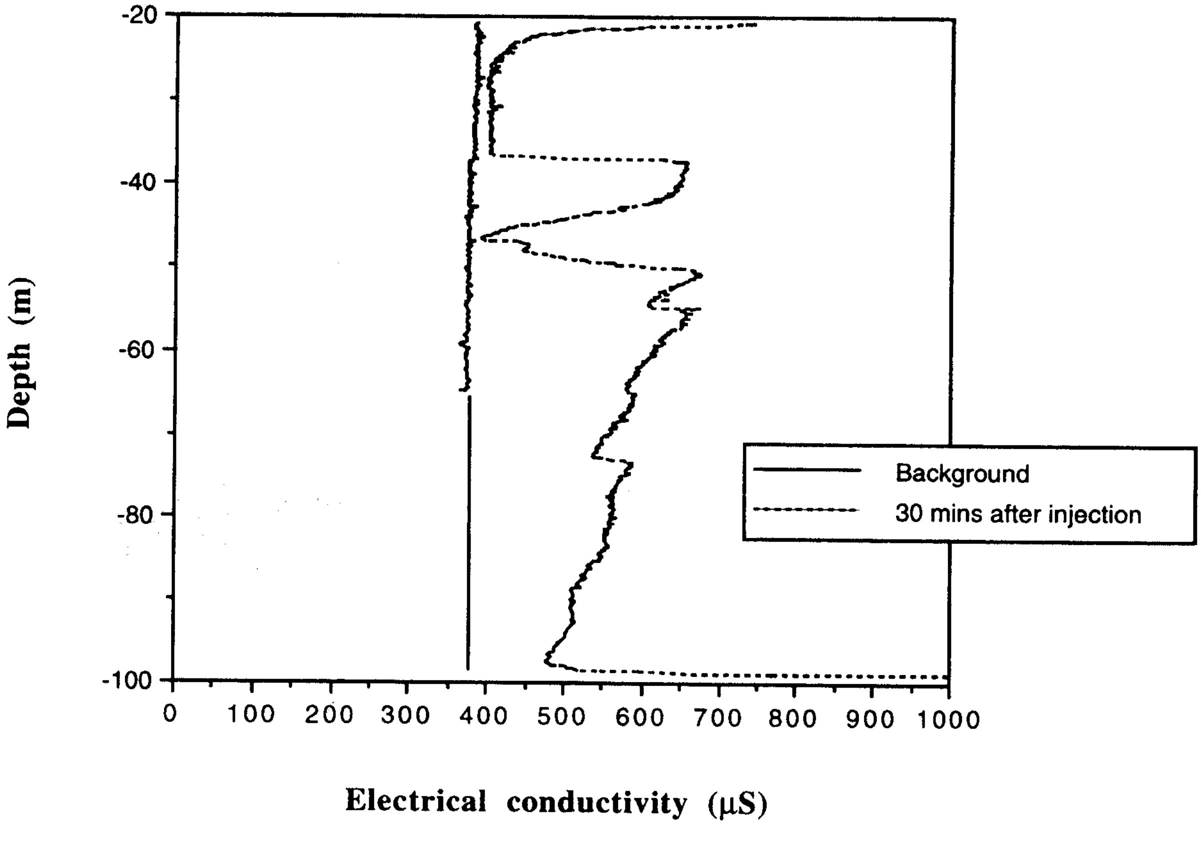
2. Cooper-Jacob (1946) with Jacob correction.

T = 0.02001 m2/s (1729 m2/d)
S = 0.004675

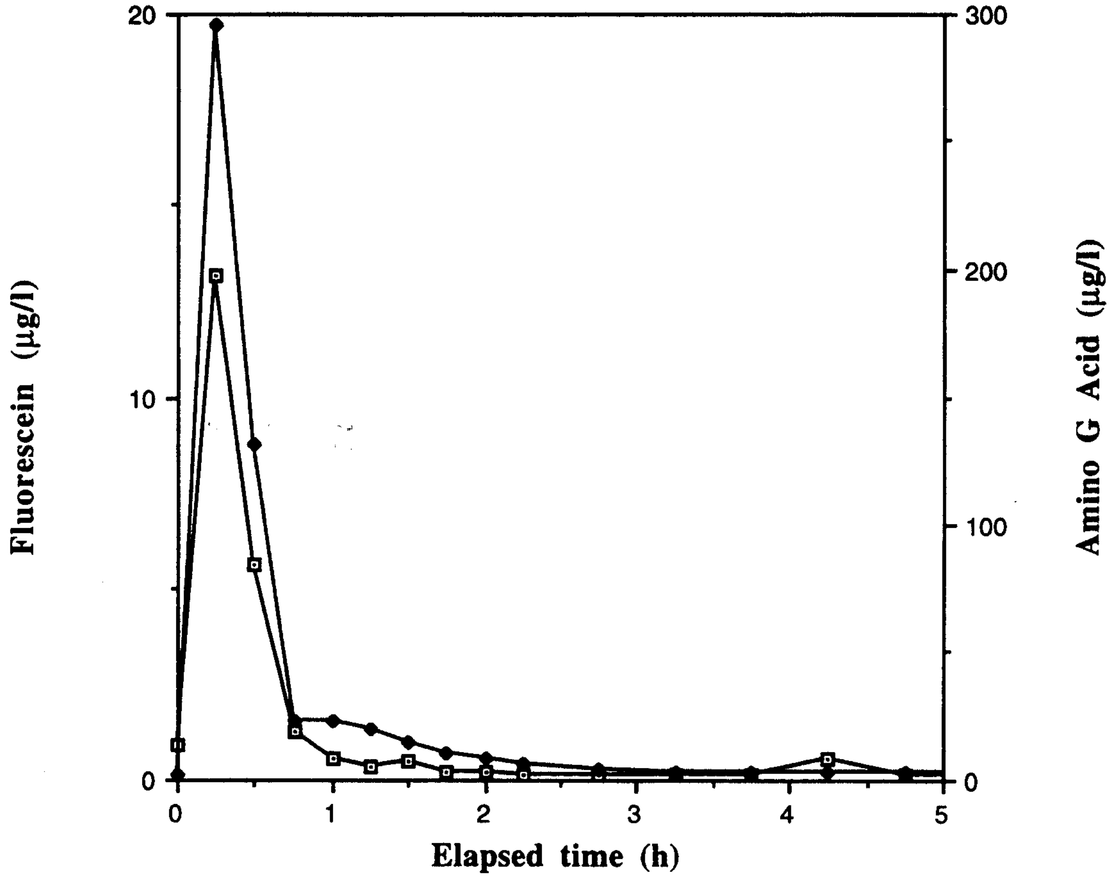
Injection borehole dilution profiles: Banterwick Barn OBH2 (BB-south).



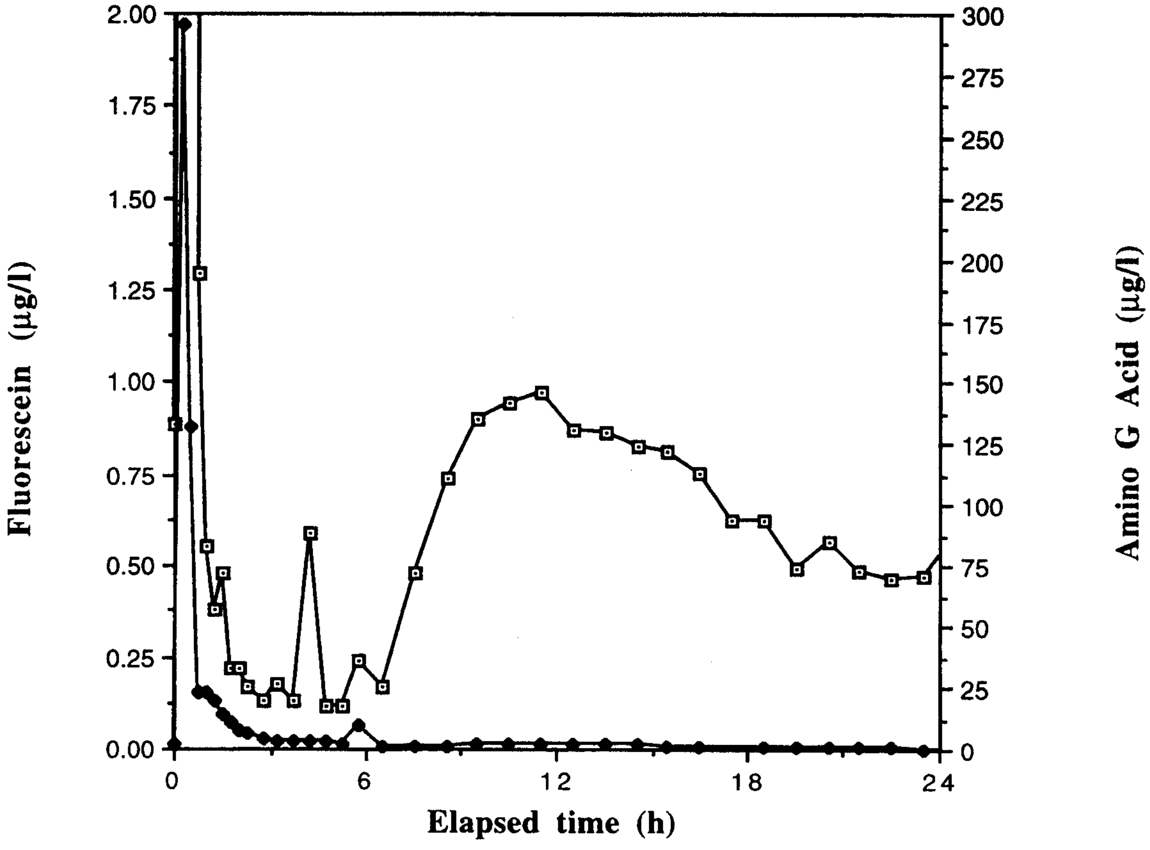
Injection borehole dilution profiles: Banterwick Barn OBH1 - (BB-west).



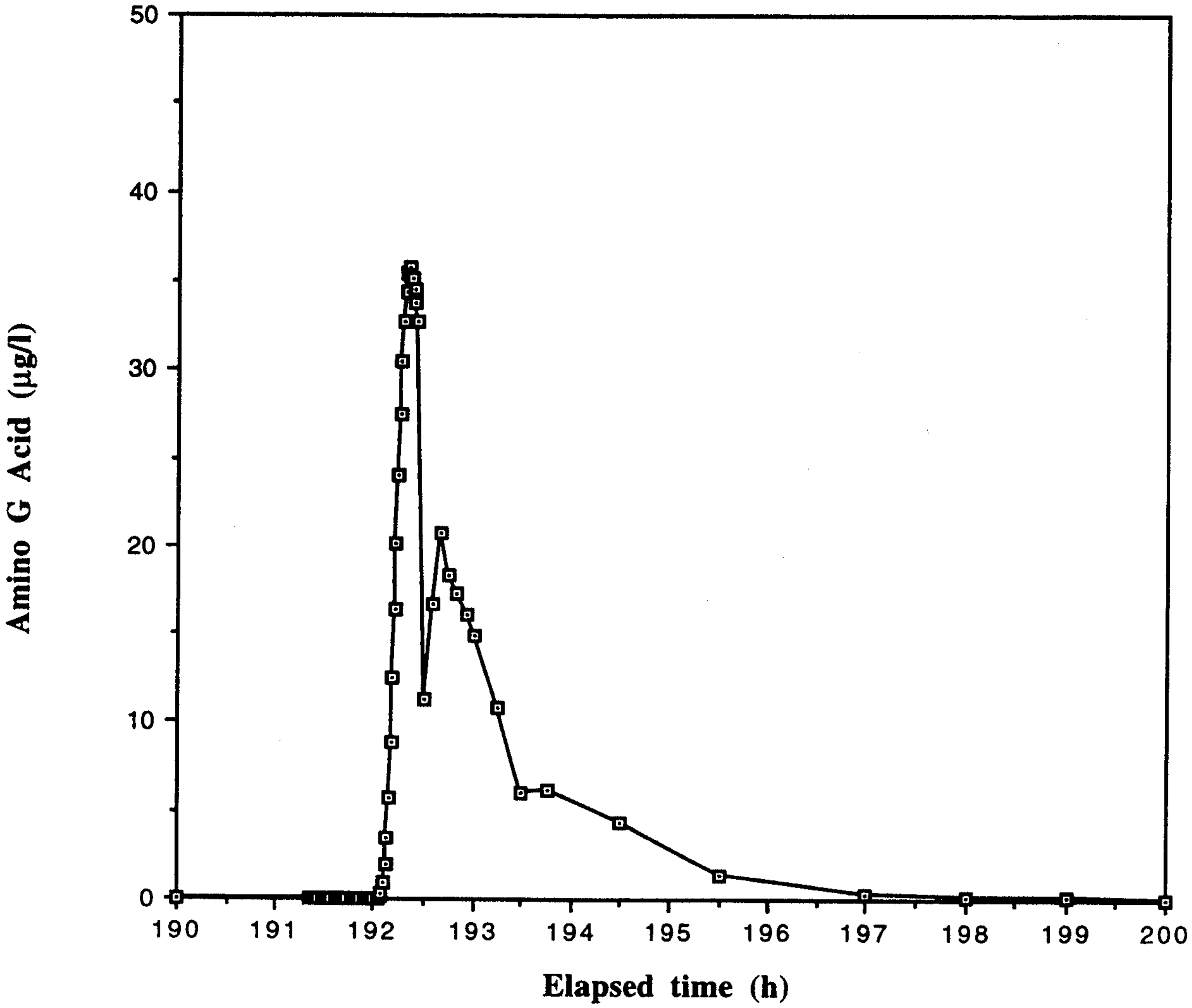
Banterwick Barn Tracer Test - Breakthrough curves (early data)



Banterwick Barn Tracer Test - Breakthrough curves (early)



Banterwick Barn Tracer Test - Late time breakthrough (>190h)



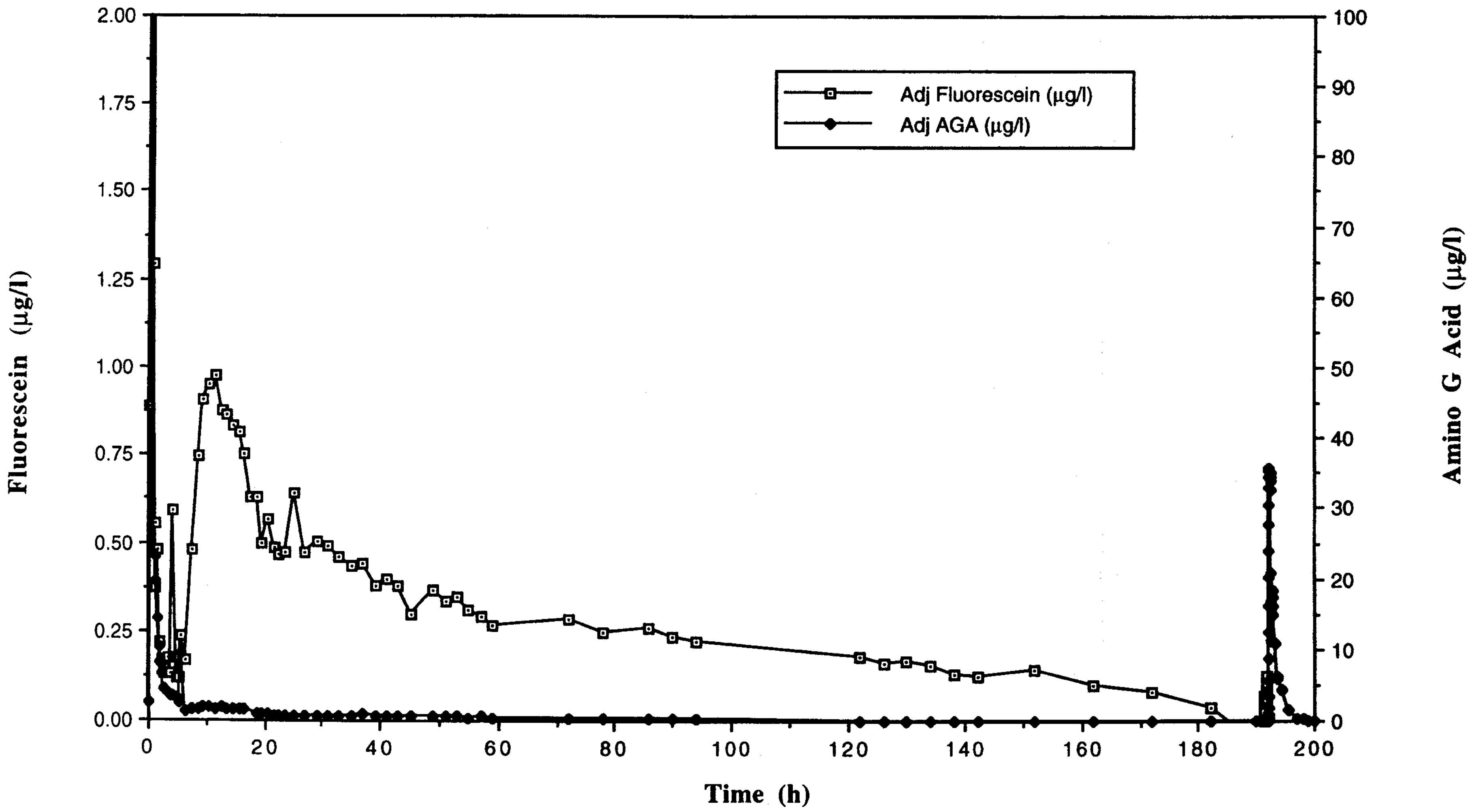
Banterwick Barn Tracer Test				
Abstraction Well Sample Data. Concentrations in µg/l.				
Injection: (i)	50 g AGA at 11:55 26-05-96 into BB-south (BH2)			
	100 g Fluorescein at 12:50 26-05-96 into BB-west (BH2)			
Injection: (ii)	50 g AGA at 14:27 30-05-96 into BB-south (BH2)			
Sample no	**Date/Time**	**Elapsed Time (h)**	**Fluorescein conc.**	**Amino G Acid conc.**
1.00	23/5/00 15:00	0.00	0.89	2.44
2.00	23/5/00 15:15	0.25	13.18	295.30
3.00	23/5/00 15:30	0.50	5.59	132.10
4.00	23/5/00 15:45	0.75	1.30	23.30
5.00	23/5/00 16:00	1.00	0.55	23.00
6.00	23/5/00 16:15	1.25	0.38	19.61
7.00	23/5/00 16:30	1.50	0.48	14.40
8.00	23/5/00 16:45	1.75	0.22	10.40
9.00	23/5/00 17:00	2.00	0.22	8.00
10.00	23/5/00 17:15	2.25	0.17	6.40
12.00	23/5/00 17:45	2.75	0.13	4.50
14.00	23/5/00 18:15	3.25	0.17	3.58
16.00	23/5/00 18:45	3.75	0.13	3.48
18.00	23/5/00 19:15	4.25	0.59	3.30
20.00	23/5/00 19:45	4.75	0.12	2.98
22.00	23/5/00 20:15	5.25	0.12	2.58
24.00	23/5/00 20:45	5.75	0.24	9.38
26.00	23/5/00 21:30	6.50	0.17	1.35
28.00	23/5/00 22:30	7.50	0.48	1.57
30.00	23/5/00 23:30	8.50	0.75	1.58
32.00	24/5/00 0:30	9.50	0.90	1.81
34.00	24/5/00 1:30	10.50	0.95	1.75
36.00	24/5/00 2:30	11.50	0.98	1.70
38.00	24/5/00 3:30	12.50	0.87	1.71
40.00	24/5/00 4:30	13.50	0.87	1.65
42.00	24/5/00 5:30	14.50	0.83	1.65
44.00	24/5/00 6:30	15.50	0.81	1.59
46.00	24/5/00 7:30	16.50	0.75	1.58
48.00	24/5/00 8:30	17.50	0.63	
50.00	24/5/00 9:30	18.50	0.63	1.06
52.00	24/5/00 10:30	19.50	0.50	0.87
54.00	24/5/00 11:30	20.50	0.57	0.91
56.00	24/5/00 12:30	21.50	0.48	0.73
58.00	24/5/00 13:30	22.50	0.47	0.68
60.00	24/5/00 14:30	23.50	0.47	0.49
62.00	24/5/00 16:00	25.00	0.64	0.50
64.00	24/5/00 18:00	27.00	0.47	0.50
66.00	24/5/00 20:00	29.00	0.50	0.57
68.00	24/5/00 22:00	31.00	0.49	0.60
70.00	25/5/00 0:00	33.00	0.46	0.69
72.00	25/5/00 2:00	35.00	0.43	0.63
74.00	25/5/00 4:00	37.00	0.44	0.85
76.00	25/5/00 6:00	39.00	0.38	0.70
78.00	25/5/00 8:00	41.00	0.40	0.66
80.00	25/5/00 10:00	43.00	0.38	0.67
82.00	25/5/00 12:00	45.00	0.30	0.66

86.00	25/5/00 16:00	49.00	0.37	0.56
88.00	25/5/00 18:00	51.00	0.34	0.53
90.00	25/5/00 20:00	53.00	0.35	0.47
92.00	25/5/00 22:00	55.00	0.31	0.45
94.00	26/5/00 0:00	57.00	0.29	0.47
96.00	26/5/00 2:00	59.00	0.27	0.38
98.00	26/5/00 17:00	72.00	0.29	0.32
100.00	26/5/00 21:00	78.00	0.25	0.27
104.00	27/5/00 5:00	86.00	0.26	0.26
106.00	27/5/00 9:00	90.00	0.24	0.21
108.00	27/5/00 13:00	94.00	0.22	0.19
110.00	28/5/00 17:00	122.00	0.18	0.14
112.00	28/5/00 21:00	126.00	0.16	0.07
114.00	29/5/00 1:00	130.00	0.17	0.10
116.00	29/5/00 5:00	134.00	0.15	0.05
118.00	29/5/00 9:00	138.00	0.13	0.03
120.00	29/5/00 13:00	142.00	0.12	0.04
121.00	29/5/00 15:00	144.00		
122.00	29/5/00 17:00	146.00		
123.00	29/5/00 19:00	148.00		
124.00	29/5/00 21:00	150.00		
125.00	29/5/00 23:00	152.00	0.14	0.08
126.00	30/5/00 1:00	154.00		
127.00	30/5/00 3:00	156.00		
128.00	30/5/00 5:00	158.00		
129.00	30/5/00 7:00	160.00		
130.00	30/5/00 9:00	162.00	0.10	0.03
131.00	30/5/00 11:00	164.00		
132.00	30/5/00 13:00	166.00		
133.00	30/5/00 15:00	168.00		
134.00	30/5/00 17:00	170.00		
135.00	30/5/00 19:00	172.00	0.08	0.01
136.00	30/5/00 21:00	174.00		
137.00	30/5/00 23:00	176.00		
138.00	31/5/00 1:00	178.00		
139.00	31/5/00 3:00	180.00		
140.00	31/5/00 5:00	182.00	0.04	-0.01
141.00	31/5/00 7:00	184.00		
142.00	31/5/00 9:00	186.00		
143.00	31/5/00 11:00	188.00		
144.00	31/5/00 13:00	190.00	-0.06	-0.04
145.00	31/5/00 14:21	191.35	0.01	0.00
146.00	31/5/00 14:22	191.37	0.02	0.02
147.00	31/5/00 14:23	191.38	0.00	
148.00	31/5/00 14:24	191.40	0.01	-0.03
149.00	31/5/00 14:25	191.42	0.00	
150.00	31/5/00 14:26	191.43	0.00	-0.07
151.00	31/5/00 14:27	191.45	0.01	
152.00	31/5/00 14:28	191.47	0.03	-0.02
153.00	31/5/00 14:29	191.48	0.03	
154.00	31/5/00 14:30	191.50	0.02	-0.06
155.00	31/5/00 14:31	191.52	0.03	

156.00	31/5/00 14:32	191.53	0.03	-0.03
157.00	31/5/00 14:33	191.55	0.05	
158.00	31/5/00 14:34	191.57	0.05	-0.04
159.00	31/5/00 14:35	191.58	0.06	
160.00	31/5/00 14:36	191.60	0.07	-0.02
161.00	31/5/00 14:37	191.62	0.06	
162.00	31/5/00 14:38	191.63	0.06	-0.06
163.00	31/5/00 14:39	191.65	0.08	
164.00	31/5/00 14:40	191.67	0.08	0.00
165.00	31/5/00 14:41	191.68	0.07	
166.00	31/5/00 14:42	191.70	0.08	-0.04
167.00	31/5/00 14:43	191.72	0.07	
168.00	31/5/00 14:44	191.73	0.07	0.05
169.00	31/5/00 14:45	191.75	0.09	
170.00	31/5/00 14:46	191.77	0.08	0.02
171.00	31/5/00 14:47	191.78	0.10	
172.00	31/5/00 14:48	191.80	0.09	-0.02
173.00	31/5/00 14:49	191.82	0.10	
174.00	31/5/00 14:50	191.83	0.09	-0.05
175.00	31/5/00 14:51	191.85	0.11	
176.00	31/5/00 14:52	191.87	0.10	-0.04
177.00	31/5/00 14:53	191.88	0.11	
178.00	31/5/00 14:54	191.90	0.12	-0.07
179.00	31/5/00 14:55	191.92	0.11	
180.00	31/5/00 14:56	191.93	0.11	0.01
181.00	31/5/00 14:57	191.95	0.13	
182.00	31/5/00 14:58	191.97		-0.05
183.00	31/5/00 14:59	191.98		
184.00	31/5/00 15:00	192.00		-0.05
185.00	31/5/00 15:01	192.02		
186.00	31/5/00 15:02	192.03		-0.08
187.00	31/5/00 15:03	192.05		-0.03
188.00	31/5/00 15:04	192.07		0.11
189.00	31/5/00 15:05	192.08		0.32
190.00	31/5/00 15:06	192.10		0.89
191.00	31/5/00 15:07	192.12		1.92
192.00	31/5/00 15:08	192.13		3.52
193.00	31/5/00 15:09	192.15		5.67
194.00	31/5/00 15:10	192.17		8.83
195.00	31/5/00 15:11	192.18		12.48
196.00	31/5/00 15:12	192.20		16.30
197.00	31/5/00 15:13	192.22		20.14
198.00	31/5/00 15:14	192.23		24.03
199.00	31/5/00 15:15	192.25		27.49
200.00	31/5/00 15:16	192.27		30.49
201.00	31/5/00 15:17	192.28		32.79
202.00	31/5/00 15:18	192.30		34.43
203.00	31/5/00 15:19	192.32		35.46
204.00	31/5/00 15:20	192.33		35.77
205.00	31/5/00 15:21	192.35		35.36
206.00	31/5/00 15:22	192.37		35.15
207.00	31/5/00 15:23	192.38		34.59
208.00	31/5/00 15:24	192.40		33.74

209.00	31/5/00 15:25	192.42		32.66
210.00	31/5/00 15:30	192.50		11.20
211.00	31/5/00 15:35	192.58		16.62
212.00	31/5/00 15:40	192.67		20.72
213.00	31/5/00 15:45	192.75		18.33
214.00	31/5/00 15:50	192.83		17.27
215.00	31/5/00 15:55	192.92		16.05
216.00	31/5/00 16:00	193.00		14.83
217.00	31/5/00 16:05	193.08		
218.00	31/5/00 16:10	193.17		
219.00	31/5/00 16:15	193.25		10.76
220.00	31/5/00 16:20	193.33		
221.00	31/5/00 16:25	193.42		
222.00	31/5/00 16:30	193.50		5.95
223.00	31/5/00 16:35	193.58		
224.00	31/5/00 16:40	193.67		
225.00	31/5/00 16:45	193.75		6.09
226.00	31/5/00 16:52	193.87		
227.00	31/5/00 16:57	193.95		
228.00	31/5/00 17:30	194.50		4.31
229.00	31/5/00 18:00	195.00		
230.00	31/5/00 18:30	195.50		1.40
231.00	31/5/00 19:00	196.00		
232.00	31/5/00 19:30	196.50		
233.00	31/5/00 20:00	197.00		0.37
234.00	31/5/00 20:30	197.50		
235.00	31/5/00 21:00	198.00		0.18
236.00	31/5/00 21:30	198.50		
237.00	31/5/00 22:00	199.00		0.09
238.00	31/5/00 22:30	199.50		
239.00	31/5/00 23:00	200.00		0.05
240.00	1/6/00 10:35	211.58		1.88
241.00	1/6/00 11:00	212.00		1.67

Banterwick Barn Tracer Test - Breakthrough curves



APPENDIX D

TRACER TEST SUMMARY SHEETS

Contents

Site No	Location	Aquifer
1	Arish Mell, Lulworth, Dorset	Chalk
2	Bedhampton and Havant springs, Hampshire	Chalk
3	Stanford Dingley, Berkshire	Chalk
4	Addington well, Croydon	Chalk
5	M1/M25 Motorway Junction	Chalk
6	Kilham, Yorkshire	Flamborough Chalk
7	North and South Mimms, Hertfordshire	Chalk
8	Horseheath, Cambridgeshire	Middle Chalk
9	West Wratting, Cambridgeshire	Chalk
10	A604 Junction, Cambridgeshire	Chalk
11	Ashdon, Cambridgeshire	Chalk
12	Stapleford, Cambridgeshire	Lower Chalk
13	Chilford Hall, Cambridgeshire	Chalk
14	Fulbourn, Cambridgeshire	Lower Chalk
15	Linton, Cambridgeshire	Middle and Lower Chalk
16	New England, Cambridgeshire	Lower Chalk
17	Eagle Lane, Cambridgeshire	Chalk
18	Cambridge Hill, Cambridgeshire	Chalk
19	Newmarket and Snailwell springs	Chalk
20	Corpusti, near Saxthorpe, Norfolk	Upper Chalk
21	Candover Catchment, Hampshire	Chalk
22	Burpham, Sussex	Chalk
23	Swaffham, Norfolk	Chalk
24	Haskayne Cutting, Ormskirk, Lancashire	Triassic Sandstone
25	Mersey Tunnel	Permo-Triassic Sandstone
26	Rickets Farm, Ashdon	Upper and Middle Chalk
27	Longwood Quarry, near Metheringham, Lincs	Lincolnshire Limestone

Site No	Location	Aquifer
28	Between Ness and Helmsley, Yorkshire	Corallian Limestone
29	Waterfoot and Carnlough, Northern Ireland	Chalk
30	Kilham, Yorkshire	Chalk
31	Hockering, Norfolk	Chalk
32	Gt Ryburgh, Norfolk	Chalk
33	N Elmham, Norfolk	Chalk
34	Etling Green, Norfolk	Chalk
35	Hockering Norfolk	Chalk
36	Costessey, Norfolk	Chalk
37	Forncett St Peter, Norfolk	Chalk
38	Bixley, Norfolk	Chalk
39	Etton	Chalk
40	Carlton, Yorkshire	Triassic Sandstone
41	Coedely, S. Wales	Spoil Heap
42	Tilmanstone, Kent	Chalk
43	Ten Acre Plantation	Upper Chalk
44	Snetterton Hall	Upper and Middle Chalk
45	Dower House	Upper Chalk
46	South Farm	Upper Chalk
47	Hockham Hall	Upper and Middle Chalk
48	Roudham	Upper Chalk

SUMMARY OF TRACER TEST INFORMATION

Site No. - 1

Aquifer

Chalk.

Location and site details

Arish Mell, Lulworth, Dorset. Injection borehole OL 14 at SY 854 807? Springs on coast to south.

Type of test

Natural gradient, borehole to spring.

Tracer used

Tracer - Rhodamine Ken-Acid.

Date of test

January 1981.

Organization carrying out test

L S Alexander, University of Bristol.

Test details

Tracer injected in borehole 400 m from coast. Springs on coast monitored.
Test 1 - 100g of dye made up to 2 litre solution poured into borehole and mixed using weighted rope.

Test 2 - three days after test 1. 50g dye injected at 25 m below borehole datum and 50g dye injected at 45 m below datum.

Spring samples taken regularly and subsequently analysed for fluorescence.

Test results and interpretation

Strong single peak of one day duration observed four days after test 1. Monitoring ceased after eighth day. Peak interpreted to mean single fissure rather than network. If peak caused by test 1 then velocity is 100 m/day. Hydraulic conductivity calculated to be 50 000 m/day.

Sources of information

Alexander, L. S. (1981) Hydrogeology of the Chalk of South Dorset. Ph.D. Thesis, Department of Geology, University of Bristol.

SUMMARY OF TRACER TEST INFORMATION

Site No. 2

Aquifer

Chalk

Location and site details

Bedhampton springs (SU 701121) and Havant springs (SU 712063), Hampshire. Springs lie at about 6 m AOD, and have a combined average flow of around 104 000 m^3/day.

Type of test and purpose

Swallow hole to spring. Purpose to prove the existence of rapid underground drainage from an area of closed depressions to the springs in order to ascertain the likely effects of using the depressions for motorway drainage.

Tracer used

Rhodamine WT.

Date of test

6 September 1974.

Organization carrying out test

T C Atkinson (University of East Anglia) and D I Smith (University of Bristol).

Test details

Tracer was injected at Hazleton Wood Swallet (SU 7011121) at around 55 m AOD. Five hundred ml of a 20% solution of dye were added to water discharged into the swallow hole (a total of 5.4 million litres of water were piped into the swallet).

Test Results

Detectable traces of dye were seen at the Bedhampton springs after 53 hours, peaking at 62.5 hours and ceasing to be detectable after 96 hours. Times for Havant springs were 67, 71 and 83 hours, with a lower peak. No tracer was seen in a borehole up-gradient. Sixty-nine per cent of injected tracer was recovered, of which 99.2% was found at Bedhampton. The distance of the input point to Bedhampton is 5.75 km, implying a peak concentration velocity of 2.21 km/day.

Sources of information

Atkinson, T. C. and Smith, D. I. (1974) Rapid groundwater flow in fissures in the Chalk: an example from South Hampshire, Quarterly Journal of Engineering Geology, 7, 197-205.

SUMMARY OF TRACER TEST INFORMATION

Site No. 3

Aquifer

Chalk, near boundary with Tertiary beds.

Location and site details

Stanford Dingley, Berkshire. Chalk spring named the 'Blue Pool'(SU 58 71), elevation 55 m AOD. The Blue Pool is part of a complex of springs with a typical total flow of 17 000 m^3/day.

Type of test and purpose

Swallow hole (SU 53 70) to spring. Purpose to determine possible cause of turbidity in Blue Pool.

Tracer used

Fluorescein.

Date of test

19 July 1988.

Organization carrying out test

Thames Water Authority.

Test details

Swallow hole at Holly Lane tested. Elevation = 78 m AOD, RWL = 72 m AOD, distance from Blue Pool = 4.7 km.

Four litres of concentrated Fluorescein solution emptied into swallow hole, washed down by a bowser of water (no streamflow into swallow hole at time of test). Samples taken from Blue Pool by automatic sampler (frequency 1.5 hours).

Test Results

Breakthrough at Blue Pool seen after around 16.5 hours, peaking at 19.5 hours; therefore maximum velocity was 6840 m/day and peak concentration velocity was5780 m/day. Curve showed little attenuation.

Sources of information

Banks, D., Davies, C. and Davies, W. (1995). The Chalk as a Karstic Aquifer: the evidence from a tracer test at Stanford Dingley, Berkshire, Quarterly Journal of Engineering Geology, 28, S31-S38.

SUMMARY OF TRACER TEST INFORMATION

Site No. 4

Aquifer

Chalk (covered with clay with flints).

Location and site details

Addington well, Croydon (TQ 371 628). Has adits?

Type of test and purpose

Forced gradient, radial flow (sinkhole to borehole). Purpose to establish possible route for pollutants.

Tracer used

Test i) Salt.
Test ii) Salt.
Test iii) Bacteria.
Test iv) Bacteria.

Date of test

1908.

Organization carrying out test

H M Richards and J A H Brinckler.

Test details

Tracer tests carried out between 'a depression'(almost certainly a sinkhole) somewhat over 3.2 km to the south of the well, and the well.

Test i) 1500 kg (1.5 tons) salt put into depression, and similar amount on surface nearby. 182 000 litres (40 000 gallons) pumped onto salt. Well pumped continuously. Well water analysed every half hour for 'chlorine' (sic) [chloride].

Test ii) 1500 kg salt washed into depression.

Test iii) Bacteria added to depression.

Test iv) Bacteria added to depression.

Test Results

Test i) Chloride detected 29.5 hours after injection of tracer (suggesting velovity of c. 2.6 km/day); peak between 38-41 hours (1.9-2 km/day).

Test ii) Rise in chloride detected 22.5 hours after injection (velocity of 3.4 km/day), with most definite results at 29 hours (2.6 km/day).

Only certain fractures in the headings showed excess chloride.

Test iii) Bacteria detected in well after 78.5 hours.

Test iv) Bacteria detected in well after 67.5 hours; maximum concentration at 78 hours after injection.

Sources of information

Whittaker, W. (1912) The water supply of Surrey from underground sources, Mem. Geol. Survey England and Wales, HMSO, London.

SUMMARY OF TRACER TEST INFORMATION

Site No. 5

Aquifer

Chalk

Location and site details

M1/M25 Motorway junction (TL 1103).

Type of test and purpose

Natural gradient tests from soakaways at motorway junction to nearby public supply boreholes. Purpose to see whether a pollutant entering the soakaways would reach public water supplies, and if it did, how long it would take.

Tracer used

Test i) Photine CU (optical brightener).
Test ii) Serratia marcescens (bacteriophage) and Escherichia coli MS2 (bacteriophage).
Test iii) Rhodamine WT.

Date of test

Test i) 2 December 1986.
Test ii) 13 May 1988.
Test iii) 20 May 1988.

Organization carrying out test

BGS/UEA/University of Surrey

Test details

Test i) Eight monitoring boreholes used (A-H). Two-month monitoring programme of boreholes before test. Six cubic metres water pumped into soakaway, then 90 kg of 20% solution of Photine CU, followed by more water.

Test ii) Monitoring began on 4 May (sites B and C), 5 May at site H. Chalk beneath soakaway saturated, then 20l suspension containing $1.1x10^{17}$ pfu of E. coli MS2 bacteriophage, followed by $8.2x10^{15}$ Serratia marcescens bacteriophage. On 20 May 13.6 m^3 water added to flush tracer into aquifer.

Test iii) Initially 15 m^3 added to soakaway. Fifty-five litres of 20% Rhodamine WT solution added with 2 m^3 water, followed by 7.6 m^3 water after 4 hours.

Test Results

Test i) Tracer was only detected at one monitoring borehole (non-pumped). Tracer detected in two pulses of low concentration, one within three days (corresponding to an average speed of at least 1 km/day) and the second within four weeks.

Test ii) Sites B, C and H monitored. Serratia marcescens bacteriophage detected at site H between 28 and 77 hours after injection (maximum velocity >100 m/hour). At site B E. Coli bacteriophage was detected after 20 days, and S. marcescens bacteriophage detected 25-33 days after injection. No bacteriophage was detected at site C.

Test iii) No Rhodamine detected at sites B, C or H.

Sources of information

Price, M., Atkinson, T. C., Barker, J.A. and Monkhouse, R. A. (1992) A tracer study of the danger posed to a chalk aquifer by contaminated highway runoff. Proc. Instn. Civ. Engrs. Wat., Marit. and Energy, 96, 9-18.

SUMMARY OF TRACER TEST INFORMATION

Site No. 6

Aquifer

Chalk (Flamborough Chalk).

Location and site details

Kilham, Yorkshire (TA 0664). Langtoft and Broachdale dry valleys converge at Kilham.

Type of test and purpose

Natural gradient tests in Langtoft and Broachdale valleys. Purpose to investigate major flow zones in the two valleys, to assist with Nitrate Sensitive Area designation around a pumping station at Kilham.

Tracer used

Langtoft Valley test - Photine CU.
Broachdale Valley test - fluorescein.

Date of test

3 March 1994.

Organization carrying out test

BGS.

Test details

Langtoft Valley Test
Twenty-five litres of 20% solution of Photine CU injected in Henpit Hole borehole. Monitoring was carried out in boreholes downgradient at distances of 40, 1500 and 2875 m from the injection point.

Broachdale Valley Test
Forty-eight litres of 1.875% solution of Fluorescein were injected into the Broachdale Borehole. Monitoring was carried out a boreholes at 1300 m and 3100 m from the injection point, and a spring 3100 m from the injection point.

Test Results

Langtoft Valley Test
Tracer arrived at the borehole 40 m from the injection borehole within 18 hours (indicating a minimum velocity of 50 m/day) and continued to be detected for around two months. No tracer was detected in the other monitoring boreholes.

Broachdale Valley Test
Tracer was possibly detected at the 3100 m borehole after between 7 and 11 days (suggesting a velocity of 280-440 m/d), and definitely after 18 days (indicating a minimum velocity of 170 m/d). Tracer was detected for at least 9 weeks. No tracer was detected at the other monitoring locations.

Source of information

Ward R. S. and Williams A. T. (1994) A tracer test in the Chalk near Kilham, North Yorkshire. Technical Report WD/95/7, British Geological Survey.

SUMMARY OF TRACER TEST INFORMATION

Site No. 7

Aquifer

Chalk

Location and site details

North and South Mimms, Hertfordshire. Two swallow hole complexes at North Mimms (Water End - TL 2304) and one complex at South Mimms. These swallow holes usually drain local streams, but occasionally are flooded. Severe overflows eventually reach the River Colne, to the west.

Type of test and purpose

Natural gradient test to determine whether swallow holes could be sources of pollution for Lee Valley waters (around 10 miles to the north-east).

Tracer used

Fluorescein.

Date of tests

Test 1 - 7 December 1927
Test 2 - 23 February 1928
Test 3 - 23 April 1932
Test 4 - 19 January 1935

Organization carrying out test

Metropolitan Water Board.

Test details

Test 1 - One pound (450 g) doses of fluorescein put into Mimmshall Brook feeding southern swallow holes at North Mimms twice daily for four days. Lee Valley and River Colne monitored.

Test 2 - Two pound (910 g) dose of fluorescein followed shortly after by one pound (450 g) dose put into northern swallow holes at North Mimms. Lee Valley and River Colne monitored.

Test 3 - Repeat of test 1, with four pounds (1820 g) of fluorescein added in one dose.

Test 4 - South Mimms swallow holes tested.

Test Results

No dye was seen in the River Colne (or associated wells?). Dye was seen in several wells and springs in the Lee Valley.

The study concluded that while the surface drainage of the Mimms area is to the Colne Valley, the subsurface drainage is to the Lee Valley. The tracer tests indicated lateral dispersion of the tracer as it moved from the swallow holes of both north and South Mimms to the north-west.

Sources of information

Morris, R. E. and Fowler, C. H. (1937) The flow and bacteriology of underground water in the Lee Valley. In 'Thirty second annual report on the results of the chemical and bacteriological examination of the London waters for the twelve months ended 31st December 1937'. Editor; C. H. H. Harold. Metropolitan Water Board, 89-99.

SUMMARY OF TRACER TEST INFORMATION

Site No. 8

Aquifer

Chalk (Middle Chalk)

Location and site details

Horseheath (TL 6147), Cambridgeshire.

One abstraction well (is this TL54/52 at Grid Ref TL 5965 4669 in the Wallingford records?) and one observation borehole serving as injection well.

Details:	**Abstraction well**	**Observation BH**
BH no.	TL 54/114	TL 54/101
Location	TL ???	TL ???
diameter	610 mm (???)	610 mm
depth	120 m	120 m
ground level (m AOD)	-	68.0 m AOD
datum (m AOD)	-	-
distance from abs. well	-	40 m (?)
RWL	-	54.92 m AOD

see attached borehole logs.
Average aquifer proeprties; T = 1385 m^2/day and S $=1.2x10^{-2}$

Type of test and purpose

(a). Single borehole dilution test under natural gradient
(b). Radially converging tracer test for characterisation of flow in Chalk (part of MPhil).

(a). Single hole natural gradient test

Tracer Used

Amino-G-Acid sufficient to raise borehole concentration to 1.5 mg/l

Date of test

10-03-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to observation borehole (TL 54/101) as a column of tracer within the saturated part of borehole using hose.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

Rapid dilution observed in bottom half of borehole below 60 m. Less rapid further up hole and almost zero at water surface (possibly in casing)

Average darcy velocity = 0.008 m/day giving an hyd. cond, k = 8.0 m/day.

(b). Radially converging tracer test

Tracer Used

500 g Fluorescein

Date of test

10-06-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to observation borehole (TL 54/101) as a column of tracer within the saturated part of borehole using hose.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile and concentration monitored frequently in abstraction well (TL54/114) to obtain BTC.

Results

Injection well dilution shows that thereare possibly two flow horizons; 25-50 m bd and 80 -100 m bd although after a few days most of the tracer has gone except at the base of the hole where concs. are nearly as high as they where at the start - dead zone.

The flow horizons within the aquifer appear to be different under natural and artificial conditions.

Tracer arrived at abstraction well very quickly, 1st arrival at ≈ 2.5 h, peak at ≈ 8.75 h (conc ≈ 160 μg/l). BTC has a long tail > 150 h. Analysis of the curve using one-dimensional Fickian dipersion model requires 2 curves (components) to be fitted. Only first component used for aquifer properties determination.

	component 1	**component 2**
mass recovered (total)	353.6 g (70%)	
Discharge	2610 m^3/day	
mass recovered 209	144.6	
transit time	9 h	65 h
dipersivity	5.72	10.89
hyd cond (m/day)	4	-
effective porosity	$1.2x10^{-3}$	-

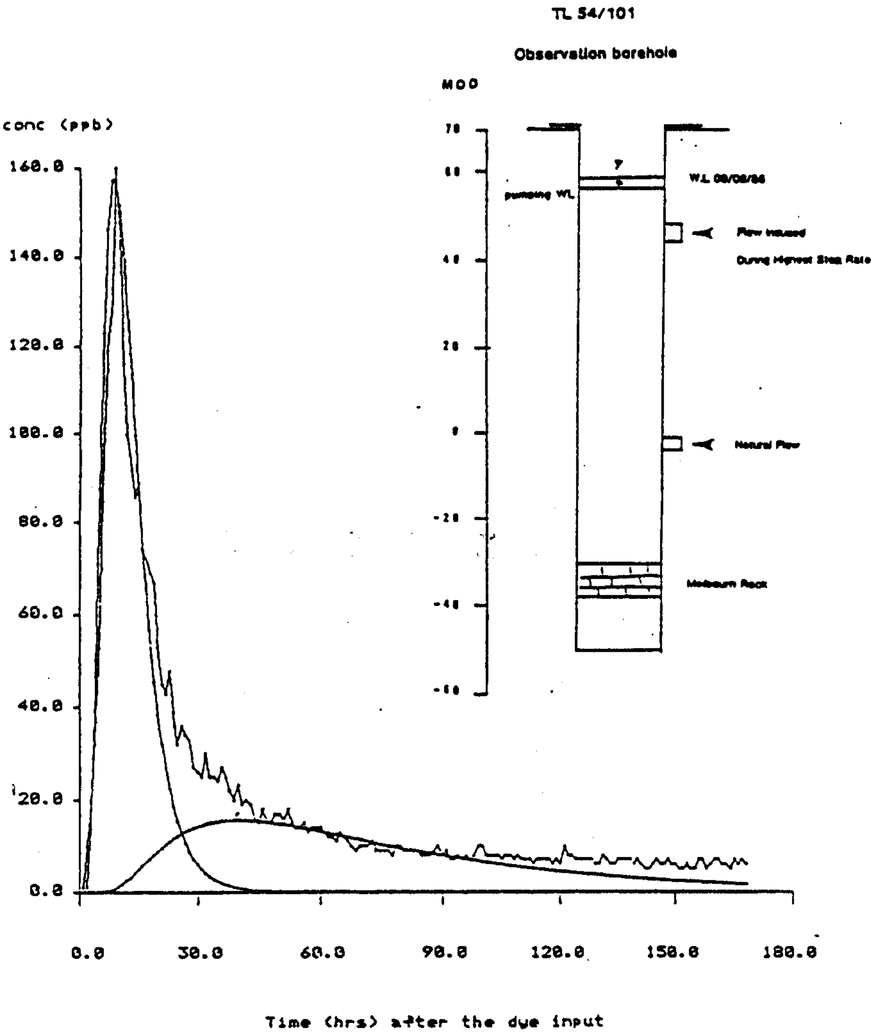
derived **fracture properties;**

paramater	planar distribution	cubical distribution
aperture	0.23 mm	0.18 mm
frequency (per m)	5.2	1.4
spacing 0.19 m	0.71 m	

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

additions - borehole logs + tracer BTC.



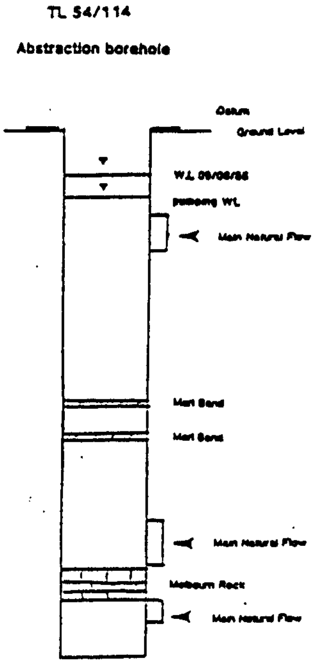
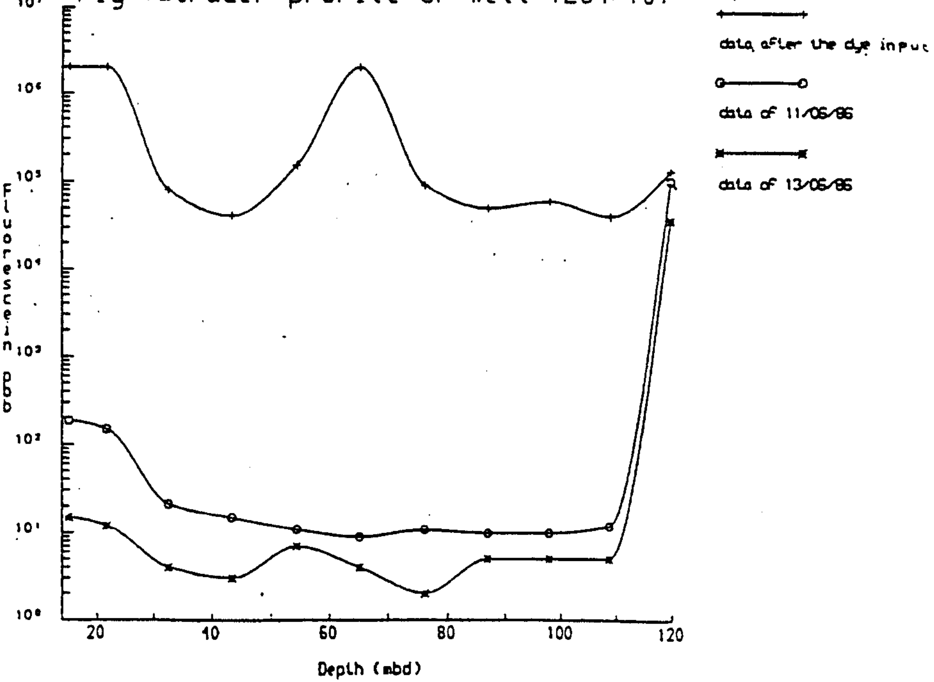


Fig.4.2tracer profile of well TL54/101



Horseheath, Cambridgeshire. Borehole Geology and results of tracer tests.

SUMMARY OF TRACER TEST INFORMATION

Site No. 9

Aquifer

Chalk (from base of Upper Chalk (Chalk Rock) through Middle Chalk and in to top of Lower Chalk)

Location and site details

West Wratting, Cambridgeshire (TL 595518).

Three boreholes: one abstraction well, one observation borehole and a nested piezometer.

Details:	**Abstraction well**	**Observation BH**	**Piezometer**
BH no.	TL 55/140	TL 55/141	TL55/155
Location	TL 59385184	TL 59525177	-
diameter	610 mm	150 mm	200 mm
depth	173 m	175 m	163 m
ground level (m AOD)	94.38	94.69	94.61
datum (m AOD)	94.77	95.38	95.11
distance from abs. well	-	134.25 m	131.8 m
distance from obs. well	134.25 m	-	1.5 m (?)

Piezometer tips at 39.37 m bd (PWT), 78 m bd (P78), 125 m bd (P125), 138 m bd (P138), 158 m bd (P158).

see attached borehole logs.

Unconfined with delayed drainage in water table zone and leaky confined between 40 to -70 m AOD.

Average aquifer properties; T = 54.1 m^2/day and S = 1.3×10^{-3}

Major fissuring is between 40 to -3 m AOD. Flow occurs between 20 to 27 m AOD and in Totternhoe Stone and Melbourn Rock.

Type of test and purpose

Radially converging tracer test for characterisation of flow in Chalk (part of MPhil).

Tracer Used

500g Fluorescein

Date of test

11-08-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to observation borehole (TL 55/141) as a column of tracer within the saturated part of borehole using hose.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile. Piezometers sampled infrequently and abstraction well sampled frequently to obain tracer breakthrough curve.

Test results

Injection well dilution shows that main dilution occurs in upper part of borehole above Marly Chalk, less between the Marly Chalk and the Melbourn Rock and even less below the Melbourn Rock.

Piezometers were sampled on three occassions. Tracer present in P125 and P159 but very low concs in P138 and P78. Infrequent sampling measn not much can be said about the piezos.

Tracer arrived at abstraction well very quickly, 1st arrival at ≈ 28 h, peak at ≈ 85 h (conc ≈ 20 μg/l). BTC has a long tail. Analysis of the curve using one-dimensional Fickian dipersion model requires 3 curves (components) to be fitted although component 3 is very small and has concs. only just above background. Therefore 2 and 3 combined. Analysis of BTC gave the following paramaters;

	component 1	component 2
mass recovered (total)	217 g (43.4%)	
Discharge	1498 m^3/day	
mass recovered 82.5	97.64	
transit time	79 h	154 h
dipersivity	6.6	8.7
hyd cond (m/day)	0.55	0.32
effective porosity	0.000895	0.001

derived fracture properties;

(a). component 1

paramater	parallel distribution	cubical distribution
aperture	0.1 mm	0.086 mm
frequency (per m)	9.0	3.48
spacing 0.11 m	0.28 m	

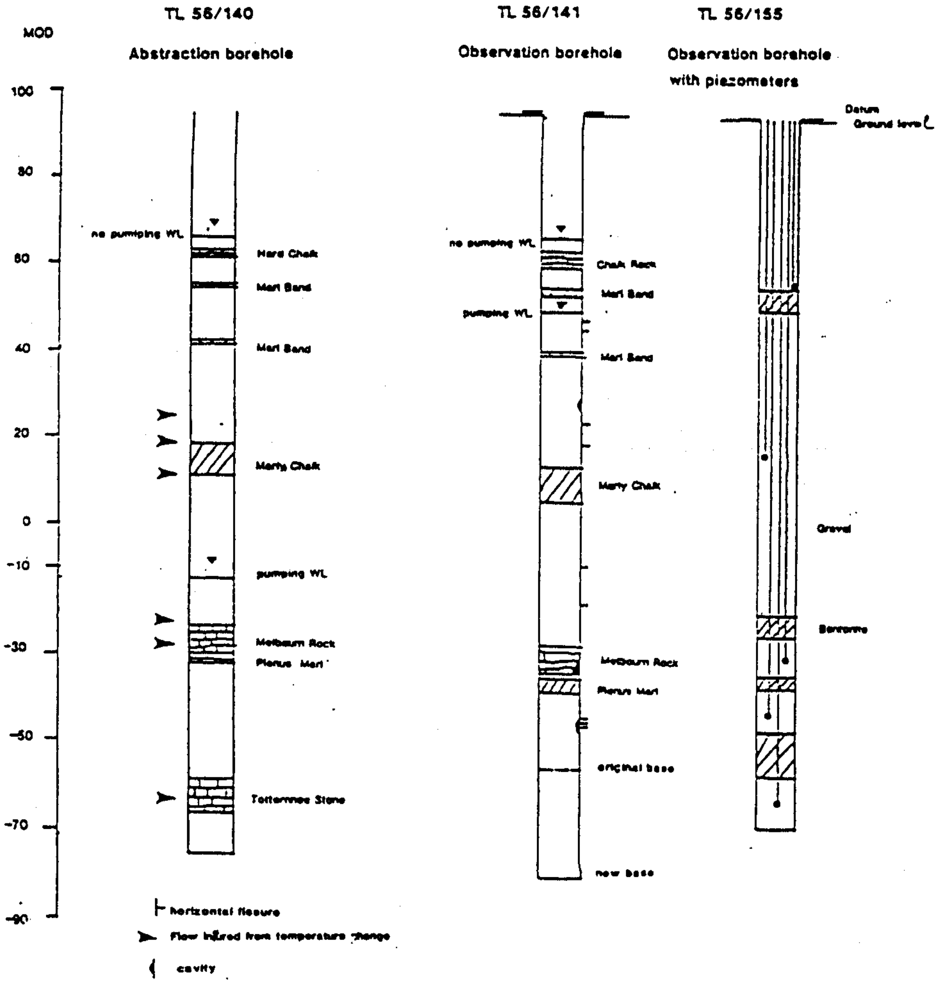
(a). component 2

paramater	parallel distribution	cubical distribution
aperture	0.072 mm	0.081 mm
frequency (per m)	13.9	4.11
spacing 0.07 m	0.24 m	

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

additions - borehole logs + tracer BTC.



	components 1	components 2'
t (hrs)	79.00	154
A $(gm^{-3}s^{1/2})$	10.67	7.45
D (m^2s^{-1})	2.78×10^{-3}	1.66×10^{-3}
V (ms^{-1})	4.19×10^{-4}	1.91×10^{-4}
D/V	6.60	8.70
M (grs)	82.50	97.64
K $(mday^{-1})$	0.55	0.32
n_e	8.95×10^{-4}	1.00×10^{-3}
planar		
b (m)	1.00×10^{-4}	7.18×10^{-5}
N (m^{-1})	9.00	13.90
n (m)	0.11	0.07
cubical		
b (m)	8.57×10^{-5}	8.11×10^{-5}
N (m^{-1})	3.48	4.11
n (m)	0.28	0.24

West Wratting, Cambridgeshire. Borehole Geology and summary of dispersion, hydraulic and physical properties.

SUMMARY OF TRACER TEST INFORMATION

Site No. 10

Aquifer

Chalk

Location and site details

A604 Junction, Cambridgeshire (TL 54/116). Grid ref TL 54?

Details:	**Injection well**
BH no.	TL 54/116
Location	TL ???
diameter	203 mm
depth	118 m
ground level (m AOD)	60.29 m AOD
RWL	54.92 m AOD

see attached borehole logs.

Type of test and purpose

Single borehole dilution test under natural gradient

Tracer Used

Amino-G-Acid sufficient to raise borehole concentration to 1.0 mg/l
Fluorescein sufficient to raise borehole concentration to 1.0 mg/l

Date of test

28-04-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to borehole as a column of tracer within the saturated part of borehole using hose such that fluorescein concentration decreased linearly with depth from 1.0 mg/l to 0 mg/l at base and amino-G-acid the opposite. The purpose to consider applicability of method for identifying and quantifying vertical flow.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

The injection described above did not seem to work ! The profiles expected were not achieved.
Lower part of borehole shows most rapid dilution (75 - 110 m bct) and slower dilution in upper part of hole except at 31.5 m where very rapid dilution occured.

seepage velocity (average) = 0.016 m/day using fluorescein
seepage velocity (average) = 0.007 m/day using amino-G-acid

$v_{31.5m}$ = 0.047 m/d (flourescein) or 0.06 m/d (AGA)

$v_{69.5m}$ = 0.027 m/d (Fl) or 0.075 m/d (AGA)
$v_{91-110m}$ = 0.015 m/d (Fl) or 0.023 m/d (AGA)

hydraulic conductivity (average) = 5.0 m/day

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

SUMMARY OF TRACER TEST INFORMATION

Site 11

Aquifer

Chalk

Location and site details

Ashdon, Cambridgeshire (TL 54/112).

Details:	**Injection well**
BH no.	TL 54/112
Location	TL575 426
diameter	200 mm
depth	140 m
ground level (m AOD)	78.81 m AOD
RWL	52.81 m AOD

Type of test and purpose

Single borehole dilution test under natural gradient

Tracer Used

5 g of Amino-G-Acid sufficient to raise borehole concentration to 1.5 mg/l

Date of test

25-02-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to borehole as a column of tracer within the saturated part of borehole using hose such that the tracer had a uniform cocentration with depth immediately after injection.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

Dilution profiles show 2 flow systems; (i). rapid dilution in upper part of borehole, 30-60 m bct at interface between Upper and Middle Chalk. (above and below Chalk Rock). (ii). Slower flow below 60 m bct towards base of hole (mainly uniform dilution).

seepage velocity (average) = 0.026 m/day (very approximate)
hydraulic conductivity (average) = 10.0 m/day

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

SUMMARY OF TRACER TEST INFORMATION

Site 12

Aquifer

Chalk (Lower Chalk)

Location and site details

Stapleford (TL 4751?), Cambridgeshire (TL 54/17).

Details:
Injection well

BH no.	TL 54/17
Location	TL???
diameter	150 mm
depth	64 m
GL (m AOD)	52.22 m AOD
RWL	9.6 m AOD

Type of test and purpose

Single borehole dilution test under natural gradient

Tracer Used

5 g of Amino-G-Acid sufficient to raise borehole concentration to 2.2 mg/l

Date of test

12-12-85

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to borehole as a column of tracer within the saturated part of borehole using hose such that the tracer had a uniform cocentration with depth immediately after injection.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

Dilution profiles show rapid dilution in upper part of borehole decreasing with depth (fairly linearly). Main dilution in Chalk above Totternhoe Stone or possibly within Totternhoe Stone. Lowest diltuion below Totternhoe Stone.

seepage velocity (average) = 0.015 m/day
velocity (upper part) = 0.019 m/d
velocity (lower part) = 0.014 m/d
hydraulic conductivity (average) = 6.0 m/day

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

SUMMARY OF TRACER TEST INFORMATION

Site 13

Aquifer

Chalk (lower Upper Chalk and Middle Chalk)

Location and site details

Chilford Hall, Cambridgeshire (TL 54/113). Is this Wallingford BH No. TL 54/46 at TL 5676 4890?

Details:
Injection well

BH no.	TL 54/113
Location	TL???
diameter	200 mm
depth	123 m
GL (m AOD)	89.27 m AOD
RWL	49.54 m AOD

Type of test and purpose

Single borehole dilution test under natural gradient

Tracer Used

5 g of Amino-G-Acid sufficient to raise borehole concentration to 1.8 mg/l
Fluorescein

Date of test

13-12-85

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Amio-G-acid tracer injected in to borehole as a column of tracer within the saturated part of borehole using hose such that the tracer had a uniform cocentration with depth immediately after injection. The fluorescein injected at the same time was injected so that it produced and initial concetration profile which decreased approximately linearly with depth from 2.4 mg/l at the top to 1.4 mg/l at the base.
Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

Very rapid dilution in upper part of borehole above Chalk Rock. Very little dilution in Melbourn Rock zone at 110 m and almost none below.

seepage velocity (average) = 0.018 m/day (Fluorescein)
seepage velocity (average) = 0.017 m/day (AGA)
vel (41-100 m) = 0.046 m/d (Fl)
vel (41-100 m) = 0.042 m/d (AGA)
hydraulic conductivity (average) = 2.0 m/day

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

SUMMARY OF TRACER TEST INFORMATION

Site 14

Aquifer

Chalk (Lower Chalk)

Location and site details

Fulbourn (TL 5156), Cambridgeshire (TL 54/154). Is this Wallingford BH No. TL 55/1 at TL 5127 5650?

Details:
Injection well

BH no.	TL 54/154
Location	TL???
diameter	200 mm
depth	30 m
GL (m AOD)	26.5 m AOD
RWL	9.34 m AOD

Type of test and purpose

Single borehole dilution test under natural gradient

Tracer Used

5 g of Amino-G-Acid sufficient to raise borehole concentration to 2.5 mg/l

Date of test

13-12-85

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to borehole as a column of tracer within the saturated part of borehole using hose such that the tracer had a uniform cocentration with depth immediately after injection.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

Complex dilution profile obtained. Maximum dilution in the middle of the Totternhoe Stone agreeingwith temperature and conductivity logs from nearby boreholes. Very little dilution at base of Totternhoe Stone snd fairly rapid dilution below it.

seepage velocity (average) = 0.0023 m/day
hydraulic conductivity (average) = 0.85 m/day

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

SUMMARY OF TRACER TEST INFORMATION

Site No. 15

Aquifer

Chalk (Middle Chalk and Lower Chalk)

Location and site details

Linton, Cambridgeshire (TL 54/28).

Details:	**Injection well**
BH no.	TL 54/28
Location	TL540 480
diameter	150 mm
depth	70 m
GL (m AOD)	33.48 m AOD
RWL	25.73 m AOD

Type of test and purpose

Single borehole dilution test under natural gradient

Tracer Used

5 g of Amino-G-Acid sufficient to raise borehole concentration to 1.0 mg/l

Date of test

12-12-85

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Amio-G-acid tracer injected in to borehole as a column of tracer within the saturated part of borehole using hose such that the tracer had a uniform cocentration with depth immediately after injection.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile.

Test results

Two zones of groundwater movement detected; (i). Middle Chalk above Melbourn Rock with uniform dilution which is relatively slow and (ii). From the Melbourn Rock to the bottom of teh hole in Lower Chalk with increasing flow with depth. Greatest flow at base below 60 m bct. Therefore Lower Chalk the major flow zone.

seepage velocity (Middle Chalk) = 0.058 m/day
seepage velocity (Lower Chalk) = 0.072 m/day
average, vel = 0.066 m/day
hydraulic conductivity (average) = 19.8 m/day

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

SUMMARY OF TRACER TEST INFORMATION

Site No. 16

Aquifer

Chalk (Lower Chalk)

Location and site details

New England, Cambridgeshire (TL 58766135).
Three boreholes: one abstraction well, one observation borehole and a nested piezometer.

Details:	Abstraction well	Observation BH	Piezometer
BH no.	TL 65/132	TL 65/122	TL -
Location	TL 58766135	TL 588615	-
diameter	610 mm	150 mm	-
depth	59.5 m	72 m	61 m
GL (m AOD)	33.04	33.18	32.57
datum (m AOD)	33.55	32.50	33.39
dist from ABH	-	177.9 m	112.3 m
dist from OBH	177.9 m	-	65.6 m

Piezometer tips at 18 m bd (PWT), 25 m bd (P25), 40 m bd (P40), 55 m bd (P55).

see attached borehole logs.

Pumping test revealed a layered unconfined aquifer with P25 and P40 representing the main saturated part of the aquifer

Average properties;
$T = 164\ m^2/day$ and $S = 4.9x10^{-2}$

Type of test and purpose

Radially converging tracer test for characterisation of flow in Chalk (part of MPhil).

Tracer Used

500g Fluorescein followed by 500g of Amino-G-acid after 7 days.

Date of test

08-19-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to observation borehole (TL 65/122) as a column of tracer within the saturated part of borehole using hose. After one week due to non-arrival at pumped well and a 24 hour failure of the pump,a second tracer (AGA) was injected.

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile. Piezometers sampled infrequently and abstraction well sampled frequently to obain tracer breakthrough curve.

Test results

Data for dilution in **injection well** shows rapid dilution which is fairly uniform but may be greatest between 25-37 m bd.

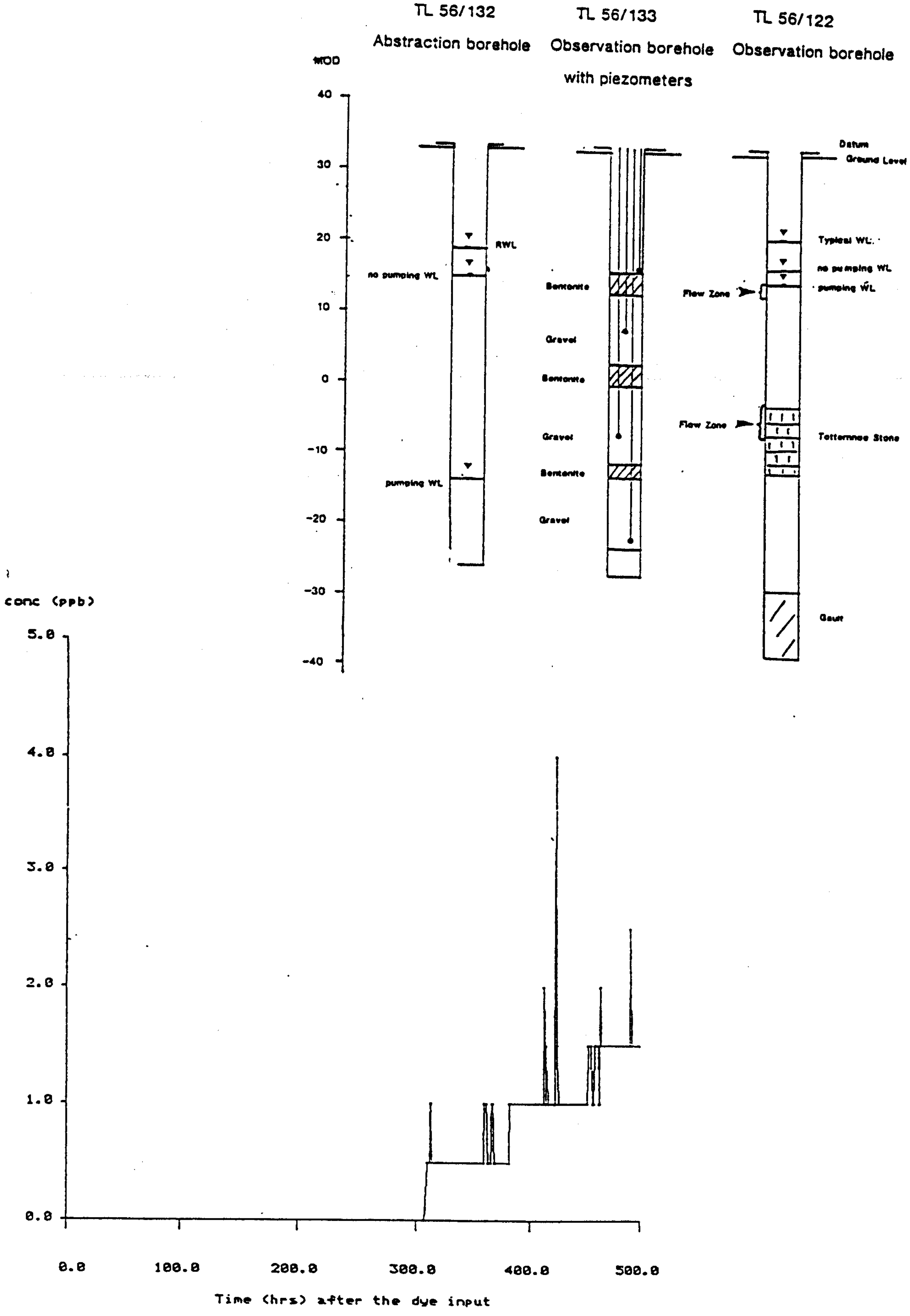
Piezometers were sampled on three occassions. Tracer present in P25 at high concs (up to 50 µg/l), P40 up to 7.5 µg/l and < 3 µg/l in P55. Poor data.

Tracer arrived at **abstraction well** but showed large scatter but definite +ve detection. Peaks uninterpretable using model. It is believed that hydraulic gradient induced was perhaps not greater enough to capture all of the tracer.

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

additions - borehole logs



New England. Borehole geology and tracer test results.

SUMMARY OF TRACER TEST INFORMATION

Site No. 17

Aquifer

Chalk (lower Middle Chalk but mainly Lower Chalk)

Location and site details

Eagle Lane, Cambridgeshire (TL 625591).

Two boreholes: one abstraction well and one observation borehole

Details:	**Abstraction well**	**Observation BH**
BH no.	TL 65/45	TL 65/44
Location	TL 625591	TL 626590
diameter	610 mm	150 mm
depth	128 m	137 m
GL (m AOD)	60.35	69.49
datum (m AOD)	60.65	68.85
dist. from ABH	-	200 m
RWL	31.84 m bd	39.42 m bd

see attached borehole logs.

Boreholes in Middle, Lower Chalk and a few metres in to the Gault Clay (base of obs. borehole). Melbourn Rock (MR) at 70-76 m bd and Totternhoe Stone (TS) at 107-111 m bd. Flow logging (BGS - 20-21/11/86) indicated major inflow within approx. 20 m above MR. Minor and major outflows also associated with MR and TS. Verical downward flow probably significant.

Aquifer unconfined with; $T = 923$ m^2/day decreasing to 516 m^2/day with time and $S = 5.9\text{x}10^{-3}$ decreasing to $2.2\text{x}10^{-3}$. (Previous test $T = 1174$ m^2/day and $S = 3.6\text{x}10^{-4}$.

Type of test and purpose

Radially converging tracer test for characterisation of flow in Chalk (part of MPhil).

Tracer Used

500g Fluorescein followed by 500g of Amino-G-acid after one week

Date of test

24-07-86

Organization carrying out test

S. Kachi (University of East Anglia) under supervision of Dr T C Atkinson (UEA)

Test Details

Tracer injected in to observation borehole (TL 65/44) as a column of tracer within the saturated part of borehole using hose. After one week because of non-arrival of tracer at abstraction well, Amino-G-acid injected at level of major flow horizon (63 m bd).

Tracer dilution in injection borehole monitored using depth sampler to give vertical dilution profile and abstraction well sampled frequently to obain tracer breakthrough curve.

Test results

Data for dilution in injection well showed rapid dilution above TS (from RWL to approx. 110 m bd) which was fairly uniform.

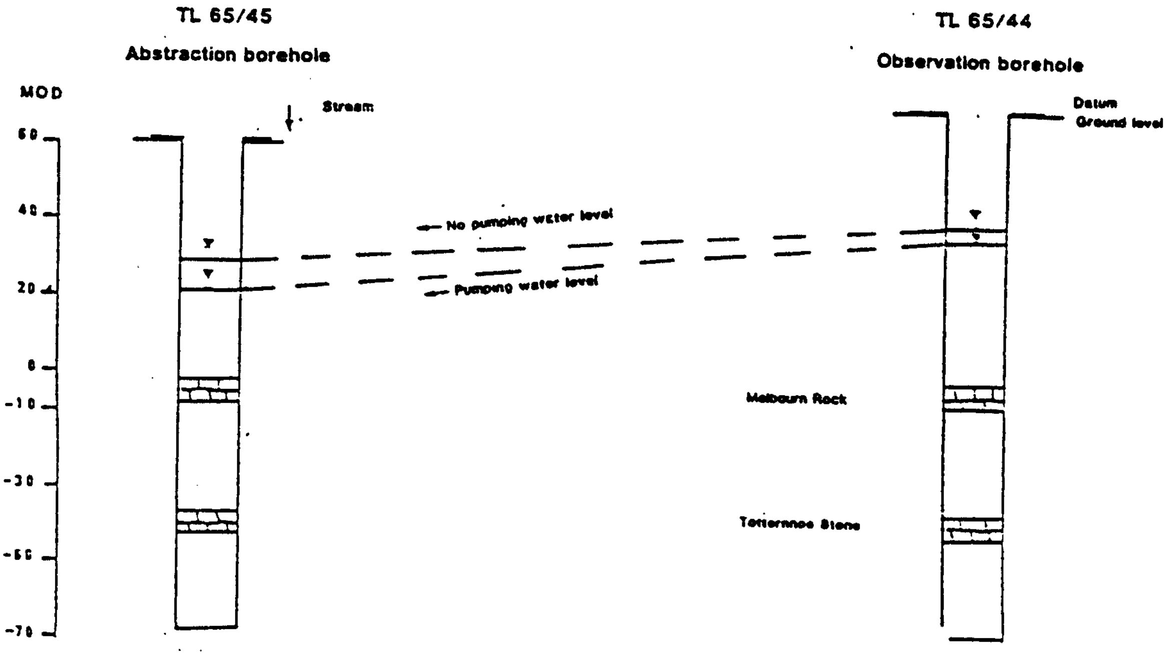
Abstraction well monitoring revealed a BTC which had scattered isolated single point peaks. Contamination of samples could be a possibility. Amino-G-acid showed same pattern. Therefore little or no tracer reached the abs. well. Rapid dilution in injection well means tracer did move however.

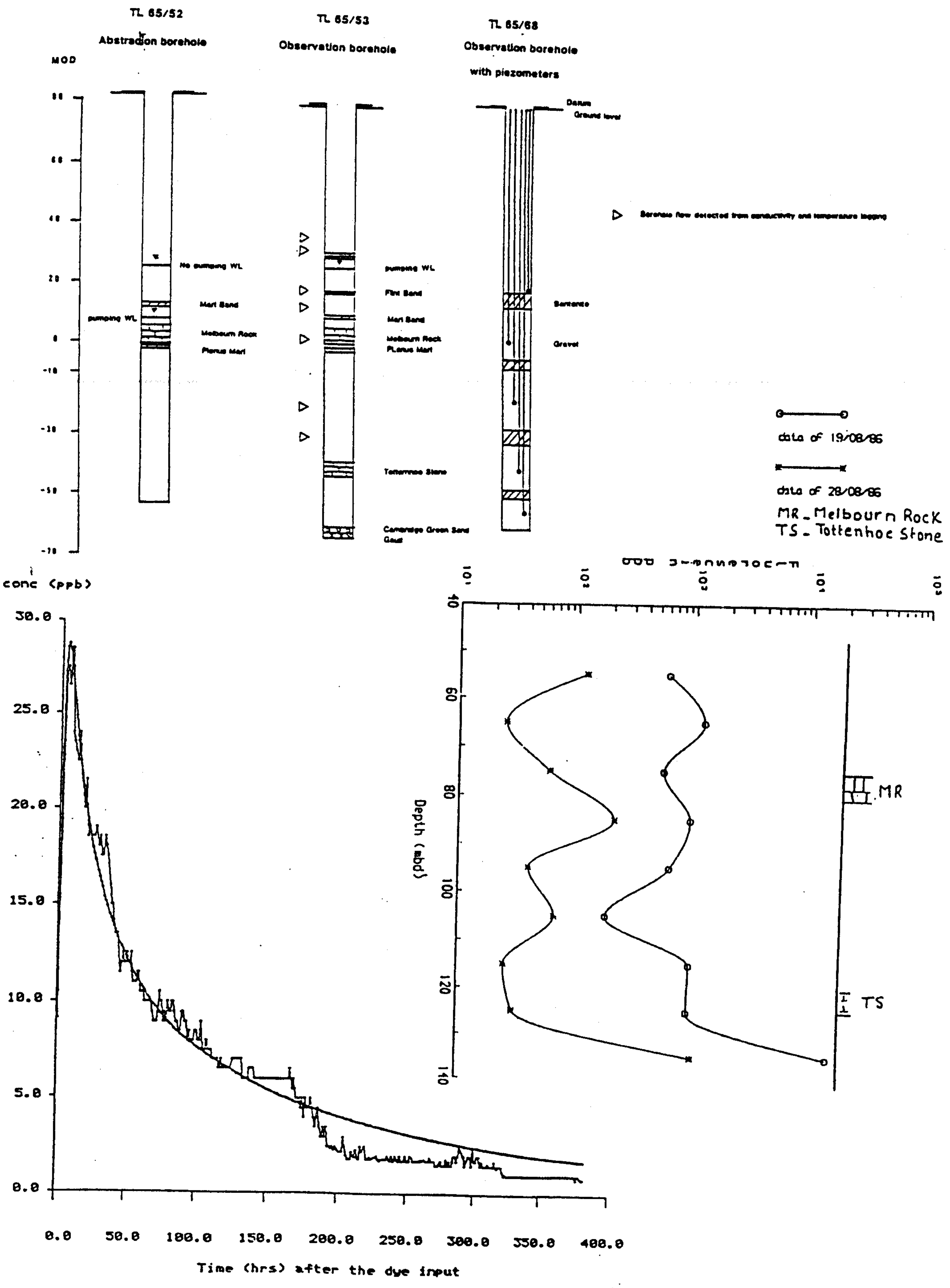
Possibly the pumping well was unable to overcome the natural or existing artificial hydraulic gradient and so tracer did not move towards abs. well. At 3 km, the Links pumping station is the nearest pumped well. This may control local gradient. One sample taken from Links did not reveal tracer - not conclusive!

Reference

Kachi S. 1987. Tracer studies in the Chalk aquifer near Cambridge. MPhil (unpublished).

additions - borehole logs





Cambridge Hill, Cambridgeshire. Borehole geology and tracer test results.

SUMMARY OF TRACER TEST INFORMATION

Site No. 19

Aquifer

Chalk

Location and site details

Newmarket (Hatchfield TL646 660) and Snailwell Springs (TL642676)

Type of test and purpose

Natural gradient point to point test to determine hydraulic connection and travel time between proposed abstraction well and springs associated with Melbourne Rock and/or Totternhoe Stone.. This was preceded by natural borehole dilution tests to determine seepage velocities and major flow horizons

Tracer used

Fluoroscein

Date

June 1987

Organization carrying out test

Mr P Sims (University of East Anglia) - BSc project

Test Details

Injection of tracer in to boreholes was by hose to give uniform concentration profile at start. Initial concentration was 0.5 g/m^3. Sampling was at 5 m intervals below the water table to base of hole.

For the point to point test, 5 kg of fluorescein made up in to a solution was injected at the major flow horizon identified by the borehole dilution test.

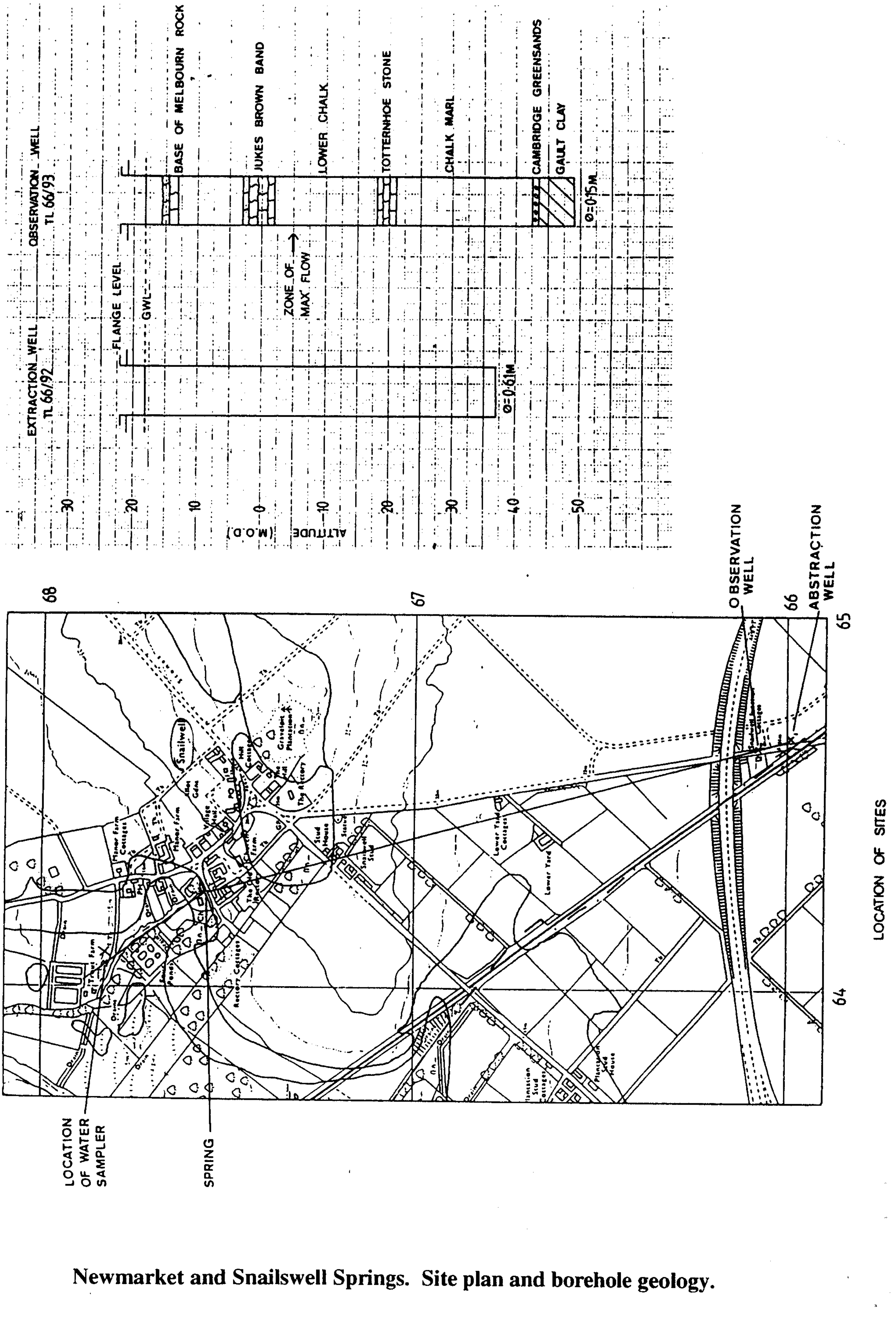
Test results

The tests proved a connection between the wells and springs although concentration of tracer which arrived were very low. The zone of strongest flow takes place in the Middle Chalk between the Jukes Browne Band and the Totternhoe Stone.

Analysis of tracer test results and pumping test results indicated the following;
hydraulic conductivity = 3.81 m/day
effective porosity = 3.8×10^{-5}
fracture aperture from 0.0013-0.0016 m
fracture spacing from 33.5 to 123 m

Source of information

T C Atkinson (UEA)



Newmarket and Snailswell Springs. Site plan and borehole geology.

SUMMARY OF TRACER TEST INFORMATION

Site No. 20

Aquifer

Chalk (Upper)

Location and site details

Corpusti (TG 1130?), near Saxthorpe, Norfolk

Site Investigation following serious subsidence which resulted in the collapse of a house. The event was apparently triggered by a pump test c. 500 m away.

Type of test and purpose

injection of tracer in to and existing borehole close to the house and subsidence area and monitoring of pumped well during pumping.

Tracer used

Rhodamine WT

Date

February 1980

Organization carrying out test

Dr T C Atkinson (University of East Anglia)

Test Details

Injection in to piezometer in hydraulic contact with upper part of Chalk in area of instability. Injection by hose pipe to open section of piezometer. Mass injected unknown. Monitoring at pumped well being used for a step pumping test (5 days duration)

Test results

No tracer recovery. Tracer still present (visible) in injection well 7 months after injection. Likely that tracer did not get in to aquifer adequately because piezometer too shallow

Source of information

T C Atkinson (personal communication)

SUMMARY OF TRACER TEST INFORMATION

Site No. 21

Aquifer

Chalk

Location and site details

Candover Catchment (SU 64?), Hampshire

Type of test and purpose

Two single borehole dilution tests to determine aquifer characteristics in the area near to the three abstraction wells. Dilution in injection wells monitored as well as arrival at pumping wells.

Tracer used

Amino G Acid and Rhodamine WT

Date

17th August 1976

Organization carrying out test

Dr T C Atkinson (University of East Anglia)

Test results

Dilution profiles obtained are not very good due to poor injection method (tipping tracer straight in to top of boreholes). Therefore there is little confidence in the results.

Results for OB7 and OB4 are as follows;

Well	seepage vel (m/day)	hyd. cond (m/day)
OB4	0.092	122.6
OB4	0.021	28.1
OB7	0.044	36.6

Tracer arrival at the three pumping wells was as follows;

Well	First arrival (days)	no. of peaks in BTC	max velocity (m/day)
Axford	7	3 major (1 minor)	163
Bradley	4	4	4750
Wield	7	4	229

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 22

Aquifer

Chalk

Location and site details

Burpham, Sussex. (TQ 0500 0940)

Type of test and purpose

To investigate the cause of periodic pollution of PWS which followed spring tides. Hypothesised that, springs on the near shore which were covered by sea water during high spring tides could result in a reversal of natural hydraulic flow especially during low water table conditions. The salt water would enter the fissure system supplying the springs and reverse the local gradient to result in movement towards the PWS.

Tracer test to test hypothesis. Tracers injected in to the springs at high spring tides and also in to a borehole to determine direction and velocity of groundwater

Tracer used

Fluorescein and Rhodamine WT

Date

July 1973

Organization carrying out test

Dr T C Atkinson (University of East Anglia)

Test results

Connection between springs and PWS at Burpham proved and so during high spring tides pollution of the PWS may occur. Flow is rapid and probably turbulent. The fissure network responsible flows below Burpham village.

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 23

Aquifer

Chalk

Location and site details

Swaffham (TF 8109?), Norfolk

Type of test and purpose

Borehole dilution test at two observation boreholes (SBH3 and SBH4) to determine seepage velocity and hydraulic conductivity of the Chalk. Also to identify layering in the Chalk.

Tracer used

Amino-G-acid

Date

March-April 1978.

Organization carrying out test

Dr T C Atkinson (University of East Anglia) for Anglian Water Authority

Test Details

Tracer injected in to the boreholes using a hose. In SBH3, 10 g of AGA in 33 litres of water was injected. Injection was over the interval 29 - 90 m bgl (RWL to 90m bgl). In SBH 4, 10 g of AGA in 10.5 litres of water was injected. Sampling was performed by taking depth samples at 5 m intervals over a period of approximately one month. A total of 4 lots of samples were taken from SBH4 and 9 from SBH3.

Test results

In SBH3, rapid dilution occurs in the upper 10-20 m of water (29-50 m bgl) suggesting more rapid movement in this zone. Dilution is exponential suggesting vertical velocities are small. In total three zones are identified.

SBH3 - zones	seepage vel (cm/day)	hyd. cond (m/day)	depth (m bgl)	AOD (m)
I	1.6-1.7	5.2-5.5	30-45	18 to 34
II	0.8-1.0	2.6-3.2	45-65	-2 to 18
III	0.4-0.7	1.3-2.3	65-104	-41 to -2

In SBH 4, rapid dilution was observed in the middle section of borehole (+1 to -9 m AOD) within the middle part of the Middle Chalk. Vertical movement indicated by the non-exponential decay of concentrations in the borehole. Best fit gives a seepage velocity of 0.024 m/day and k = 8.3 m/day.

Source of information

Dr T C Atkinson Report for AWA.
Tracer investigations of groundwater movement in two boreholes in the Chalk at Swaffham, Norfolk.

SUMMARY OF TRACER TEST INFORMATION

Site No. 24

Aquifer

Triassic sandstone (Ormskirk Sandstone), overlain by drift (c.10 m generally, 1 m at site in railway cutting).

Location and site details

Haskayne Cutting, 5km WNW of Ormskirk, Lancashire. Grid Ref. SD 356 090. Various boreholes in bottom of disused railway cutting. Site well characterised by geophysical logs, core and pumping tests.

Type of test

Radial converging forced gradient (piezometer to Borehole).

Tracers used

Fluorescein, Amino-G-Acid and bromide

Date of test

9-13 August 1994

Organization carrying out test

H Green, University of Birmingham.

Test details

Tracers were injected into a piezometer at 7 m depth. Water was pumped (flow rate 0.75 l/s) and sampled from 8-inch diameter borehole 5 m away (above packer set at 15 m) for 74 hours.

Tracer injection: 6 litres tracer mixture washed out by 1 litre fresh water.
Tracer concentration: 2 g/l fluorescein, 2 g/l amino-G-acid, 12g/l potassium bromide.

Test Results

Breakthrough curves for the fluorescent dyes show multiple concentration peaks. Fastest breakthrough showed a velocity of 51 m/day, over 20 times faster than slowest pulse. One dimensional analytical model (Halevy and Nir, 1962) suggests at least four different routes between injection and monitoring points, with fastest pulse representing 6% of the flow and the slowest pulse representing 66% of the flow. The model suggests that the kinematic porosity is 12.5% (the total porosity was 22%).

Source of information

Green, H. (1994) A tracer test in the Triassic Sandstone at Haskayne Cutting, West Lancashire. M.Sc. Thesis, Department of Geological Sciences, University of Birmingham.

SUMMARY OF TRACER TEST INFORMATION

Site No. 25

Aquifer

Permo-Triassic sandstone.

Location and site details

Mersey Tunnel (SJ 3389?).

Type of test

Gradient test, borehole to tunnel.

Tracer used

Fluorescein?

Date of test

?

Organization carrying out test

University of Leeds

Test details

?

Test Results

Tracer velocity of 140 m/d found.

Sources of information

John Tellam (Birmingham University, Pers. comm.)

Newton, R. (1993) The chemistry of a saline-freshwater mixing zone beneath Liverpool. M.Sc. Thesis, Department of Earth Sciences, University of Leeds.

SUMMARY OF TRACER TEST INFORMATION

Site No. 26

Aquifer

Upper and Middle Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - Rickets Farm, Ashdon
Borehole WRB No. - TL 54/121
Grid Reference - TL 576 425

Injection borehole (OBH)
Borehole WRB No. - TL 54/112
Grid Reference - TL 575 425
Depth - 130 m
Distance from pumped borehole - 163 m
Depth of injected tracer column - 100 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

June 1985

Organization carrying out test

R. Ward, University of East Anglia.

Test details

ABH Pumping rate - 35 l/s.

<u>Test procedure summary</u>
1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.

Test Results

25% of tracer recovered in ABH. Tracer arrived at ABH after 14.5 hours, rising to a peak at 23.5 hours. Subsequent, lower peaks occurred at 36 and 52 hours, after which the concentration fell and was continuing to fall at the end of the test, at 120 hours.
Modelling of results suggested four sets of fractures with differebt physical properties.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

SUMMARY OF TRACER TEST INFORMATION

Site No. 27

Aquifer

Lincolnshire Limestone (Jurassic)

Location and site details

Longwood Quarry, Near Metheringham, Lincs. (TF 062 593)

Purpose drilled suite of boreholes (19 in total) in the floor of the quarry to a maximum depth of approximately 20 m (base of the Limestone). Borehole diameters range from 152-203 mm and rest water level varies between 0.0 and 5.0 m below ground level depending on season.

The boreholes were drilled around a central well at distances ranging from 1 to 40 m. In addition to vertical boreholes, two inclined (30 deg) boreholes were drilled.

Type of test and purpose

Two series of tests were performed using the array. The first series consisted of a several small scale tests over distances up to 5 m tracing along a single, isolated (using packers) bedding plane fissure. The tests were radially converging tests. The second series of tests were fully penetrating larger scale tests over distances of 20 and 40 m. Again these were radially converging tests.

The purpose of testing was to investigate the controls on fluid and contaminant transport in a dual porosity aquifer.

Tracers used

Up to 20 g Fluorescein, 50 g Amino G Acid, 5 g Rhodamine WT and 250 g bromide

Date of test

September, 1995 and July, 1996

Organisation carrying out tests

British Geological Survey

Test details

Series 1. A single bedding plane fissure was isolated using packers and this bedding plane pumped. Tracer was injected in to a number of satellite boreholes (to the pumping well) at different orientations and distances and the breakthrough and concentration monitored a the pumping well. Water in the injection borehole was circulated using a peristaltic pump and a tracer pulse was injected directly into the re-circulating water. Tracer dilution in the injection well was also monitored.

Series 2. Tracer was injected into four satellite boreholes, two at 20 m and two at 40 m from a central abstraction well. Tracer was injected into the full saturated thickness of the aquifer and re-circulation of the injection well water ensured mixing and enabled a dilution profile to be obtained. Tracer breakthrough was monitored at the abstraction well using an 'in-line' fluorimeter and ion-selective electrode. Real time breakthrough curves were obtained. Prior to injection of the fluorescent tracer a bromide pulse was injected to optimise the experimental conditions.

Test Results

Series 1. Tracer breakthrough was obtained for most of the tracer injections, however, in one case the bedding plane fissure was not open but infilled with silty material (fissure infill) and tracer breakthrough did not occur. Bedding plane fissures displayed channelling.

Series 2. Tracer breakthrough was obtained for all four injections. Transit times were extremely rapid and dominated by one major bedding plane fissure. Model predictions of tracer breakthrough for the 40 m injection based on the results of the 20 m tests were poor. The breakthrough curves indicated significant tailing which could not be explained by matrix diffusion alone. Other mechanisms must therefore be operating, e.g. channelling, dead zones etc.

References/contacts

Dr R S Ward
Fluid Processes and Waste Management Group
BGS, Keyworth

SUMMARY OF TRACER TEST INFORMATION

Site No. 28

Aquifer

Corallian Limestone (Jurassic)

Location and site details

Between Ness and Helmsley, Yorkshire. River Rye (SE 690 790)

PWS abstraction well abstracting water from the Corallian Limestone for domestic supply.
A number of 8 and 12 inch observation boreholes up gradient (Golden Square, West Newton Grange and Nunnington).
Sink holes in bottom of river (Duncombe Park)
Springs down gradient of PWS well (East Ness)

Type of test and purpose

Injection of tracer into observation boreholes and river bottom sink hole to investigate the capture zone of the PWS well. The two observation borehole injection points (Nunnington and Golden Square) are both within the modelled capture zone of the Ness PWS well. Earlier borehole dilution testing indicated that Nunnington and golden Square boreholes were potentially good injection boreholes but West Newton Grange was not.

Tracers used

Bacteriophage: approximately 10^{12} pfu/ml of MS2, *Enterobacter Clocae* and *Serratia Marcesens*

Date of test

February 1997.

Organisation carrying out tests

British Geological Survey/Environment Agency

Test details

Tracer was injected into the major flow horizons of the observation boreholes (as determined by the borehole dilution tests) and poured into a suitable sink hole in the River Rye on the Duncombe Park Estate.

Sampling was performed at the PWS well (by sampling the discharge water), the spring discharge at East Ness and the River Rye (at the Ness gauging station). In each case automatic water samplers were employed.

Test results

None of the tracers were detected at either the springs or Ness PWS well. A possible explanation for non-detection at Ness PWS well is that contamination of the sampled water by chlorine may have occurred.

References/contacts

Dr R S Ward
Fluid Processes and Waste Management Group
BGS, Keyworth

SUMMARY OF TRACER TEST INFORMATION

Site No. 29

Aquifer

Chalk (Ulster White Limestone), N. Ireland

Location and site details

Waterfoot and Carnlough, N. Ireland.

Type of test and purpose

Natural gradient tracer test with injection into sink holes along the Blackburn Rivere (?), a river towards the south end of Tower Road, Crearlagh Burn and Cushenilt Burn. Monitoring was at 16 sites (springs). The purpose was to primarily establish contact between the various sinks and springs and thus direction of groundwater flow. It was also hoped that the type of flow may derived.

Tracer used

Fluorescein, rhodamine WT, diphenyl brilliant flavine (DY96) and photine CU

Date

7th August 1994

Organization carrying out test

Mr Stephen Barnes (University of East Anglia), MSc Project

Test Details

Tracers were injected in to the sink holes in the stream floors (500g of fluorescein, 150 ml Rhodamine WT (20% solution), 200g of DY96 and and 1 litre of Photine CU (20%)). Cotton wool passive detectors were used for detection of DY96 and Photine CU and activated charcoal detectors for fluorescein and rhodamine WT.

Test results

Breakthrough occured at 4 locations. Volumes of water in conduit systems have been estimated and it has been found that the volume of water entering the sink holes and being disharged at the springs is nearly equal indicating the absence of an major underground tributaries. Estimates of conduit radius range from 0.64 - 0.89m. Linear velocities reanged from 338 - 1058 m/day.

Source of information

Mr S Barnes (MSc Thesis).

SUMMARY OF TRACER TEST INFORMATION

Site No. 30

Aquifer

Chalk (East Yorkshire)

Location and site details

Kilham, Yorkshire (TF 0599 6480)

PWS well at Kilham providing local supply and series of observation boreholes along two dry valleys, the interfluve between and springs down gradient have been used to perform a series of tracer tests.

Type of test and purpose

The purpose of the testing was to investigate the capture and protection zones for the Kilham PWS well. Kilham is a designated Nitrate Sensitive Area and the modelled NSA and capture zones do not correspond. Tracer testing has been used as a validation tool. Single borehole dilution testing, point to point and tracing to the PWS well and springs have been undertaken.

Tracers used

Bacteriophage: approximately 10^{12} pfu/ml of MS2, *Enterobacter Cloca* and *Serratia Marcesens*
Fluorescent tracers: 250 g Fluorescein, 250 g Photine CU

Date of test

March 1994, January/February 1996, October, 1996 to January 1997

Organisation carrying out tests

British Geological Survey

Test details

Initially two tracer tests between observation boreholes along the two dry valleys were undertaken to characterise the hydrogeological controls in the area. Tracer injections of fluorescein and photine CU were performed in the upper reaches of the valleys into observation boreholes. Tracer was allowed to move under the natural/prevailing gradient and sampling down gradient was performed using passive detectors (cotton wool for photine and charcoal for fluorescein). The results form this confirmed that a larger scale test was feasible.

Additional boreholes were drilled and a larger scale tracer test was performed by injecting tracers into observation boreholes in the valley floor and the interfluve and sampling at Kilham PWS well, observation boreholes down gradient and springs. Tracer injections were focused on active flowing fissure horizons previously identified by single borehole dilution testing. Sampling at the PWS well, observation boreholes and springs was by automatic water sampler.

Test results

Connections along the valley floor were proven with velocities of up to 400 m/day observed. Flow appeared to be dominated by a few discrete fissures. No tracer was detected at Kilham PWS but tracer was detected further down gradient form an injection in the interfluve borehole. To reach the sampling location the tracer must have moved below or around the PWS well and not entered its capture zone. The result was confirmed by a repeat test. No tracer was detected at the PWS well. The results of the testing indicated that complex hydrogeological conditions exist in the area and the capture/protection zones may not be adequately defined.

References/contacts

Dr R S Ward, Fluid Processes and Waste Management Group
BGS, Keyworth

SUMMARY OF TRACER TEST INFORMATION

Site No. 31

Aquifer

Chalk

Location and site details

Well No. 1. Hockering, Norfolk. Grid ref. TG 17 12?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.076 m/day
Hydraulic conductivity	3.80 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 32

Aquifer

Chalk

Location and site details

Well No. 2. Gt. Ryburgh, Norfolk. Grid ref. TF 95 27?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.010 m/day
Hydraulic conductivity	0.63 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 33

Aquifer

Chalk

Location and site details

Well No. 3. N. Elmham, Norfolk. Grid ref. TF 98 20?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.008 m/day
Hydraulic conductivity	1.00 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 34

Aquifer

Chalk

Location and site details

Well No. 4. Etling Green, Norfolk. Grid ref. TG 01 13?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.004 m/day
Hydraulic conductivity	1.30 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 35

Aquifer

Chalk

Location and site details

Well No. 5. Hockering, Norfolk. Grid ref. TG 06 13?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.015 m/day
Hydraulic conductivity	0.94 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 36

Aquifer

Chalk

Location and site details

Well No. 7. Costessey, Norfolk. Grid ref. TG 17 11?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.040 m/day
Hydraulic conductivity	5.00 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 37

Aquifer

Chalk

Location and site details

Well No. 10. Forncett St. Peter, Norfolk. Grid ref. TM 16 93?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.0033 m/day
Hydraulic conductivity	1.00 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 38

Aquifer

Chalk

Location and site details

Well No. 11. Bixley, Norfolk. Grid ref. TG 25 05?

Type of test and purpose

One of a series of single borehole natural gradient dilution tests designed to produce a distribution of hydraulic conductivity and seepage velocity within an area of the Norfolk Chalk.

Tracer used

Fluorescein

Date

August 1977

Organization carrying out test

Mr I F Spratley (University of East Anglia), BSc project report

Test details

This was one of eleven wells selected for single borehole tests, of which eight yielded useable results. The tracer was injected via a container lowered down the borehole to one third depth. The container was inverted to tip out the tracer, pulled up to the surface and then dropped to the bottom of the borehole to facilitate mixing.

Dye was made up to produce a 1 ppm tracer concentration within the saturated column of borehole immediately after injection.

Test results

Velocity	0.042 m/day
Hydraulic conductivity	7.90 m/day

Source of information

Dr T C Atkinson (University of East Anglia).

SUMMARY OF TRACER TEST INFORMATION

Site No. 39

Aquifer

Chalk

Location and site details

Etton (SE 98 43?). Pumped borehole with two OBH at 100 m and 200m.

Type of test and purpose

Forced gradient radial test from two observation boreholes to a pumped borehole?

Tracer used

Phage? 10E14 PFU. Presumably different types in each OBH.

Date of test

Not known

Organization carrying out test

Not known

Test details

Tracer injected into both OBH. ABH pumped at 70 l/s?

Test Results

Tracer arrived from 100 m OBH after 0.1 days with o.5% ultimately recovered, and from 200 m OBH after 0.21 days with 0.4% finally recovered.

Sources of information

BGS display board. H Skilton PhD to be obtained.

SUMMARY OF TRACER TEST INFORMATION

Site No. 40

Aquifer

Triassic sandstone

Location and site details

Carlton, Yorkshire (SE 64 23?). ABH with OBH at 150 m and surfavce soakaway at 220 m.

Type of test and purpose

Forced gradient test

Tracer used

Phage?

Date of test

26 May 1983

Organization carrying out test

BGS/Yorkshire Water Authority

Test details

ABH pumped at c. 80 l/s? Tracer injected in OBH and soakaway?

Test Results

Travel time from soakaway was 227 days, and from OBH was 143 days. Little tracer recovery.

Sources of information

BGS display board. Test data file. More information to be obtained.

SUMMARY OF TRACER TEST INFORMATION

Site No. 41

Aquifer

Spoil heap (NCB tip)

Location and site details

Coedely Spoil Heap (NCB Tip No. 214). Frid ref. ST 01 85?

Type of test and purpose

To trace shallow groundwater movement beneath the tip.

Tracer used

Bacteriophage

Date of test

not known

Organization carrying out test

Sir William Halcrow and Partners

Test details

See paper

Test Results

See paper

Sources of information

Martin, R. and Thomas, A. 1974. An example of the use of bacteriophage as a groundwater tracer. Journal of Hydrology, 23, 73-78.

SUMMARY OF TRACER TEST INFORMATION

Site No. 42

Aquifer

Chalk

Location and site details

Tilmanstone, Kent (TR 30 51?). A saline groundwater plume has developed in the Chalk aquifer around the Tilmanstone Colliery.

Part of the pollution was caused by the discharge of saline water from Snowdown Colliery, where 40 000 tons of chloride entered the aquifer, mainly between 1926 and 1935. The Wingham public supply borehole was affected by the pollutant.

Most of the pollution was from Tilmanstone colliery, where 318 000 tons of chloride entered the aquifer between around 1900 and 1974. The Eastry public supply borehole and the North and South streams were affected by the pollutant.

Type of test and purpose

Monitoring and modelling of the saline groundwater plume from Collieries at Snowdown and Tilmanstone.

Tracer used

Saline water pollutant plume.

Date of test

Monitoring period unknown.

Organization carrying out test

Water Research Centere.

Test details

Monitoring details unknown. See paper for model calibration details.

Test Results

Monitoring details unknown. See paper for model calibration details.

Sources of information

Bibby, R. 1981. Mass transport of solutes in dual porosity media. Water Resources Research, 17, 1075-1081.

SUMMARY OF TRACER TEST INFORMATION

Site No. 43

Aquifer

Upper Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - Ten Acre Plantation - well 3A
Borehole WRB No. - TL 98/24
Grid Reference - TL 9862 8423

Injection borehole (OBH)
Borehole WRB No. - TL 98/3
Grid Reference - TL 9885 8297
Depth 32.9 m - 32.9 m
Distance from pumped borehole - 347 m
Depth of injected tracer column - 13 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

April 1986

Organization carrying out test

R. Ward, University of East Anglia.

Test details

One of a series of tracer tests in the area.
ABH Pumping rate - 50 l/s.

Test procedure summary

1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.

Test Results

No tracer recovered from ABH.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

SUMMARY OF TRACER TEST INFORMATION

Site No. 44

Aquifer

Upper and Middle Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - Snetterton Hall - Well 11A
Borehole WRB No. - TL 99/26
Grid Reference - TL 9941 9120

Injection borehole (OBH)
Borehole WRB No. - TL 99/1
Grid Reference - TL 9947 9104
Depth - 29.3 m
Distance from pumped borehole - 170 m
Depth of injected tracer column - 14 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

February 1986

Organization carrying out test

R. Ward, University of East Anglia.

Test details

ABH Pumping rate - 50.5 l/s.

Test procedure summary

1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.
6. Sampling of nearby springs and river water as appropriate.

Test Results

All tracer recovered in ABH. No tracer seen in springs. Tracer arrived at ABH after 12 hours; peaked at 110 hours (with several intermediate smaller peaks); fell to background levels after 500 hours. Modelling of results suggested seven sets of fractures with different physical properties.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

SUMMARY OF TRACER TEST INFORMATION

Site No. 45

Aquifer

Upper Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - Dower House - Well 7A
Borehole WRB No. - TL 98/26
Grid Reference - TL 9695 8548

Injection borehole (OBH)
Borehole WRB No. - TL 98/6
Grid Reference - TL 9715 8532
Depth - 24.4 m
Distance from pumped borehole - 256 m
Depth of injected tracer column - 18.5 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

1986?

Organization carrying out test

R. Ward, University of East Anglia.

Test details

ABH Pumping rate - 47 l/s.

Test procedure summary

1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.
6. Sampling of nearby river water.

Test Results

60% of tracer recovered in ABH. No tracer seen in springs. Tracer arrived at ABH after 18 hours, subsequently rising and falling, sometimes to background levels several times until 88 hours when background levels were reached. A second arrival occured at 111 hours followed by a second set of peaks until 190 hours. Background levels were finally reached after around 400 hours.
Modelling of results suggested fifteen sets of fractures with different physical properties.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

SUMMARY OF TRACER TEST INFORMATION

Site No. 46

Aquifer

Upper Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - South Farm - Well 8A
Borehole WRB No. - TL 98/27
Grid Reference - TL 9877 8944

Injection borehole (OBH)
Borehole WRB No. - TL 98/7
Grid Reference - TL 9896 8938
Depth - 41.9 m
Distance from pumped borehole - 199 m
Depth of injected tracer column - 16 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

1986?

Organization carrying out test

R. Ward, University of East Anglia.

Test details

ABH Pumping rate - 38.5 l/s.

Test procedure summary

1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.
6. Sampling of nearby river water.

Test Results

30% of tracer recovered in ABH. Tracer arrived at ABH after 32 hours, rising to a peak (in detail a set of peaks) at 93 hours and subsequently falling, and apparently continuing to fall at the end of the test at 500 hours. Modelling of results suggested one set of fractures.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

SUMMARY OF TRACER TEST INFORMATION

Site No. 47

Aquifer

Upper and Middle Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - Hockham Hall - Well 17A
Borehole WRB No. - TL 99/22
Grid Reference - TL 9515 9150

Injection borehole (OBH)
Borehole WRB No. - TL 99/6
Grid Reference - TL 9539 9164
Depth - 41.1 m
Distance from pumped borehole - 273 m
Depth of injected tracer column - 15 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

August 1986

Organization carrying out test

R. Ward, University of East Anglia.

Test details

ABH Pumping rate - 58 l/s.

Test procedure summary
1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.

Test Results

No tracer was recovered in ABH. Tracer moved only very slowly from OBH.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

SUMMARY OF TRACER TEST INFORMATION

Site No. 48

Aquifer

Upper Chalk

Location and site details

Abstraction Borehole (ABH)
Site Name - Roudham - Well 9A
Borehole WRB No. - TL 98/30
Grid Reference - TL 9638 8722

Injection borehole (OBH)
Borehole WRB No. - TL 98/8
Grid Reference - TL 9627 8710
Depth - 34.1 m
Distance from pumped borehole - 163 m
Depth of injected tracer column - 25 m

Type of test and purpose

Radially converging tracer test from OBH to ABH.

Tracer used

Fluorescein, 500g in 30 l distilled water.

Date of test

November 1985

Organization carrying out test

R. Ward, University of East Anglia.

Test details

ABH Pumping rate - 62 l/s.

Test procedure summary
1. Injection of tracer into OBH.
2. Sampling of tracer profile in OBH.
3. Automatic samplers started at ABH.
4. ABH pumping started.
5. Periodic sampling of OBH.

Test Results

No tracer was recovered in ABH. Tracer moved only very slowly from OBH.

Sources of information

R. Ward. 1989. Artificial tracer and natural ^{222}Rn studies of the East Anglian Chalk aquifer. PhD thesis, School of Environmental Sciences, University of East Anglia.

APPENDIX E

TRACER DATABASE

The tables contained in this Appendix are derived from the Tracer Database compiled during the study. The first table lists tracers by **Name** and also gives the tracer **type**. Subsequent tables group tracers by **type**. The tables are arranged in the following order.

Name
Dye
Fluorocarbon
Gas
Ion
Microorganism
Particle
Radioisotope
Stable isotope
Water temperature

Name

Tracer name	Type
131I	Radioisotope
131I	Radioisotope
133 Xe	Gas
133Xe	Radioisotope
133Xe	Radioisotope
13C	Stable Isotope
14/15N	Stable Isotope
14C	Radioisotope
18O	Stable Isotope
198Au	Radioisotope
198Au	Radioisotope
222 Rn	Gas
222Rn	Radioisotope
22Na	Radioisotope
24Na	Radioisotope
24Na	Radioisotope
2H	Stable Isotope
32/34/36S	Stable Isotope
32Si	Radioisotope
36Cl	Radioisotope
39Ar	Radioisotope
3H	Radioisotope
46Sc	Radioisotope
46Sc	Radioisotope
5(6)-carboxyfluorescein trisodium salt	Dye
82Br	Radioisotope
82Br	Radioisotope
85 Kr	Gas
85Kr	Radioisotope
85Sr	Radioisotope
Aerobacter aerogenose 243	Microorganism
Amino G acid	Dye
ammonium	Ion
Ar	Gas
b: f2	Microorganism
bacteria (general)	Particle
bacteria (general)	Microorganism
bacteria: E.coli	Microorganism
bacteria: E.coli	Particle
bacteriophage	Microorganism
benzoate	Ion
borax	Ion
bromide	Ion
BS3a	Microorganism
Calcofluor White ST	Dye
CBr2F2	Fluorocarbon
CBrClF2	Fluorocarbon
CBrI-CBrF2	Fluorocarbon
chloride	Ion

Tracer name	Type
CO	Gas
dichromate	Ion
Diphenyl Brilliant Flavine 7GFF	Dye
EDTA-46Sc	Radioisotope
EDTA-51Cr	Radioisotope
EDTA-60Co	Radioisotope
EDTA-60Co	Radioisotope
Eosine Y	Dye
f1	Microorganism
float	Particle
Fluolite BW	Dye
fluorescent polystyrene microspheres	Particle
fluorobenzoates	Ion
Freon-11	Fluorocarbon
Freon-113	Fluorocarbon
Freon-12	Fluorocarbon
Freon-13	Fluorocarbon
He	Gas
iodide	Ion
Kr (stable)	Gas
Leucophor B	Dye
Leucophor BCF	Dye
Leucophor BS	Dye
Leucophor C	Dye
Leucophor CK	Dye
Lissamine FF	Dye
lithium	Ion
lithium chloride	Ion
lithuim bromide	Ion
Lycopodium spores	Microorganism
magnesium	Ion
Naphthionate	Dye
Ne	Gas
NO	Gas
paper	Particle
Photine CSP	Dye
Photine CU	Dye
PM6c	Microorganism
PM7a	Microorganism
potassium	Ion
potassium chloride	Ion
Pyranine	Dye
Rhodamine B	Dye
Rhodamine WT	Dye
SF6	Gas
signal-emitting float	Particle
sodium chloride	Ion
spores: lycopodium	Particle
strontium	Ion

Tracer name	Type	Tracer name	Type
Succinylfluorescein disodium salt	Dye		
Sulforhodamine B	Dye		
Sulforhodamine G	Dye		
sulphate	Ion		
T4	Microorganism		
T7	Microorganism		
thiocyanate	Ion		
Tinopal CBS-X	Dye		
Uranine (Sodium Fluorescein)	Dye		
v: bovine Enterovirus	Microorganism		
v:poliovirus	Microorganism		
VH5a	Microorganism		
viruses	Particle		
viruses	Microorganism		
Water temperature	Water temperature		
Xe (stable)	Gas		
yeast	Particle		
yeast	Microorganism		

Dye

tracer name	5(6)-carboxyfluorescein trisodium salt
colour index	
chemical formula	$C_{21}H_{9}O_{7}Na_{3}$
molecular weight	442.27 (16)
background level	
detection limit (ppb)	0.01 (16)
max excitation wavelength (nm)	494
max emission wavelength (nm)	515
solubility	623 g/l @ 20°C
sorption tendency	Kd=0.03-0.53 cm3/g; rd=1.36 (16)
photochemical instability	k=0.018-0.021 (16)
effect of pH	max fluorescence intensity >pH9
environmental/health effects	not toxic to goldfish or crucians
commercial form	
manufacturer	

tracer name	Amino G acid
colour index	
chemical formula	$C_{10}H_{9}NO_{6}S_{2}$
molecular weight	303 (4)
background level	variable
detection limit (ppb)	0.51 (3)
max excitation wavelength (nm)	355(310)
max emission wavelength (nm)	445
solubility	
sorption tendency	low (1)
photochemical instability	low (3)
effect of pH	fluorescence affected below pH6
environmental/health effects	probably non-mutagenic; LC50>1000 mg/l (21)
commercial form	powder
manufacturer	

tracer name	Calcofluor White ST
colour index	CI 40622; Fluorescent Brightener 28
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	
max excitation wavelength (nm)	
max emission wavelength (nm)	
solubility	
sorption tendency	
photochemical instability	
effect of pH	
environmental/health effects	LD50=14.5 g/kg (rat), non-carcinogenic; LC50>1000 mg/l (bluegill) (21)
commercial form	
manufacturer	

tracer name	Diphenyl Brilliant Flavine 7GFF
colour index	CI Direct Yellow 96
chemical formula	
molecular weight	
background level	variable
detection limit (ppb)	
max excitation wavelength (nm)	
max emission wavelength (nm)	
solubility	
sorption tendency	
photochemical instability	
effect of pH	
environmental/health effects	LD50>15 g/kg (rat);LC50>1000 mg/l (rainbow trout) (21)
commercial form	
manufacturer	

Dye

tracer name	Eosine Y
colour index	CI 45380; Acid Red 87
chemical formula	C20H6Br4O5Na2
molecular weight	691.88 (4)
background level	variable
detection limit (ppb)	1.0 (6); 0.01 (5)
max excitation wavelength (nm)	516
max emission wavelength (nm)	537
solubility	high (6)
sorption tendency	low (5); rd=40-214 (18); Kd=0-0.03 cm3/g (7)
photochemical instability	very high (5)
effect of pH	moderately pH dependent (20)
environmental/health effects	LD50>1 g/kg (rat) (17,21); possibly mutagenic; LC50>100 mg/l (rainbow trout) (21)
commercial form	powder
manufacturer	

tracer name	Fluolite BW
colour index	CI Fluorescent Brightener 49
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	
max excitation wavelength (nm)	355 (15)
max emission wavelength (nm)	435 (15)
solubility	
sorption tendency	
photochemical instability	k=0.031 (15)
effect of pH	fluorescence falls rapidly below pH 7
environmental/health effects	low toxicity
commercial form	powder
manufacturer	ICI Ltd

tracer name	Leucophor B
colour index	CI Fluorescent Brightener 49?
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	
max excitation wavelength (nm)	
max emission wavelength (nm)	
solubility	
sorption tendency	
photochemical instability	
effect of pH	
environmental/health effects	low toxicity
commercial form	powder
manufacturer	Sandoz Chemical Products Ltd

tracer name	Leucophor BCF
colour index	- (optical brightener)
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	100 (13)
max excitation wavelength (nm)	
max emission wavelength (nm)	
solubility	1 g/l (13)
sorption tendency	
photochemical instability	high (13)
effect of pH	
environmental/health effects	low toxicity
commercial form	
manufacturer	

Dye

tracer name	Leucophor BS
colour index	CI Fluorescent Brightener 49
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	
max excitation wavelength (nm)	355 (15);405 @ 1 mg/l; 335 @ 0.5 mg/l (14)
max emission wavelength (nm)	435 (15);445 @ 1 mg/l; 430 @ 0.5 mg/l (14)
solubility	
sorption tendency	
photochemical instability	
effect of pH	
environmental/health effects	LD50=8 g/kg (15);LD50>8 g/kg (14); low toxicity, not carcinogenic; should pose no health hazard to human or animal in concentrations used, especially given rapid photodegradation rate
commercial form	25% solution
manufacturer	Sandoz Chemical Products Ltd (no longer available, 15)

tracer name	Leucophor C
colour index	CI Fluorescent Brightener 232
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	
max excitation wavelength (nm)	405 @ 40 mg/l (14)
max emission wavelength (nm)	465 @ 40 mg/l (14)
solubility	
sorption tendency	
photochemical instability	
effect of pH	
environmental/health effects	LD50=8 g/kg
commercial form	40% solution (14); 25% solution (15)
manufacturer	Sandoz Chemical Products Ltd (no longer available, 15)

tracer name	Leucophor CK
colour index	CI Fluorescent Brightener 232
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	
max excitation wavelength (nm)	
max emission wavelength (nm)	
solubility	
sorption tendency	
photochemical instability	
effect of pH	
environmental/health effects	LD50>8 g/kg; low toxicity, not carcinogenic; should pose no health hazard to human or animal in concentrations used, especially given rapid photodegradation rate
commercial form	powder
manufacturer	Sandoz Chemical Products Ltd

tracer name	Lissamine FF
colour index	CI 56205; Acid Yellow 7
chemical formula	C18H15O8N2SNa
molecular weight	
background level	variable
detection limit (ppb)	0.29 (3); 0.03 (5)
max excitation wavelength (nm)	420
max emission wavelength (nm)	515
solubility	
sorption tendency	medium (5)
photochemical instability	very low (5)
effect of pH	stable between pH4 - pH10
environmental/health effects	LD50=8.6 g/kg (rat) (17,21); possibly mutagenic; LC50>1000 mg/l (rainbow trout) (21)
commercial form	powder
manufacturer	Brico Commercial Chemicals Co Ltd

Dye

tracer name	Naphthionate
colour index	-
chemical formula	C10H8O3NSNa
molecular weight	
background level	relatively high background signals in UV range caused by strong light scattering (7)
detection limit (ppb)	0.07 (5); 0.3-0.5 (raised by high background in natural waters) (7)
max excitation wavelength (nm)	325
max emission wavelength (nm)	420
solubility	240 g/l @ 21°C (7)
sorption tendency	low (5); rd=1.0; Kd=0-0.1 cm3/g (7)
photochemical instability	moderate (5); t½=3.7xt½(uranine)
effect of pH	stable between pH 6 to 8.5
environmental/health effects	
commercial form	
manufacturer	

tracer name	Photine CSP
colour index	CI Fluorescent Brightener 145
chemical formula	
molecular weight	
background level	variable, high
detection limit (ppb)	
max excitation wavelength (nm)	350
max emission wavelength (nm)	438; 455 (15)
solubility	
sorption tendency	
photochemical instability	k=0.056 (15)
effect of pH	stable between pH6 to pH9
environmental/health effects	low toxicity; LD50=16 g/kg
commercial form	approx. 40% powder, mixed with NaCl
manufacturer	Hickson and Welch Ltd

tracer name	Photine CU
colour index	CI Fluorescent Brightener 15
chemical formula	
molecular weight	
background level	variable, high in industrial or domestic effluent
detection limit (ppb)	0.36 (3)
max excitation wavelength (nm)	345
max emission wavelength (nm)	435(455)
solubility	
sorption tendency	
photochemical instability	high (3); k=0.064 (15)
effect of pH	fluorescence affected below pH6.5
environmental/health effects	low toxicity
commercial form	20% solution in urea, with ethanolamine
manufacturer	Hickson and Welch Ltd

tracer name	Pyranine
colour index	CI 59040; Solvent Green 7
chemical formula	C16H7O10S3Na3
molecular weight	524.38 (4)
background level	variable
detection limit (ppb)	0.087 (3); 0.008 (5)
max excitation wavelength (nm)	455(405)
max emission wavelength (nm)	515
solubility	178 g/l @ 20°C(8)
sorption tendency	very low (5); Kd=0.03-0.24 cm3/g (7)
photochemical instability	high (5)
effect of pH	large variation in fluorescence with pH; most suitable dye for use at low pH (10)
environmental/health effects	LD50>16 g/kg (rat), 10.5 g/kg (mouse) (8)
commercial form	powder
manufacturer	Bayer Dyestuffs Ltd

Dye

tracer name	Rhodamine B
colour index	CI 45170; Basic Violet 10
chemical formula	C28H31N2O3Cl
molecular weight	479.02 (4)
background level	variable
detection limit (ppb)	0.011-0.021 (6); 0.01 (3); 0.006 (5)
max excitation wavelength (nm)	554
max emission wavelength (nm)	576
solubility	20 g/l (6)
sorption tendency	strong (5); Kd=4.8-8.6 cm3/g (7)
photochemical instability	very low (5); k=0.0015 (15)
effect of pH	fluorescence affected below pH5
environmental/health effects	carcinogenic, possibly mutagenic; LD50=0.9 g/kg (mouse) (17,21);>0.5 g/kg(rat); LC=155-506 mg/l(21)
commercial form	powder; acetic acid
manufacturer	

tracer name	Rhodamine WT
colour index	CI Acid Red 388
chemical formula	C29H29N2O5Na2Cl (3,6,9); C29H29N2O5Na (4)
molecular weight	508 (4)
background level	variable
detection limit (ppb)	0.01-0.05 (6); 0.013 (3); 0.006 (5)
max excitation wavelength (nm)	554
max emission wavelength (nm)	572
solubility	
sorption tendency	medium (5)
photochemical instability	very low (5)
effect of pH	fluorescence affected below pH5
environmental/health effects	LD50>25 g/kg (rat) (17,21); possibly carcinogenic; possibly non-mutagenic; LC>320 mg/l (rainbow trout) (21)
commercial form	sodic solution
manufacturer	Crompton and Knowles Ltd

tracer name	Succinylfluorescein disodium salt
colour index	
chemical formula	C16H10O5Na2
molecular weight	328.23 (16)
background level	
detection limit (ppb)	0.05 (16)
max excitation wavelength (nm)	490
max emission wavelength (nm)	506
solubility	335 g/l @ 20°C
sorption tendency	Kd=0.00-1.32 cm3/g; rd=1.34 (16)
photochemical instability	k=0.030-0.032 (16)
effect of pH	max fluorescence intensity >pH8.5
environmental/health effects	not toxic to goldfish or crucians
commercial form	
manufacturer	

tracer name	Sulforhodamine B
colour index	CI 45100; Acid Red 52
chemical formula	C27H30N2O7S2Na2 (6); C27H29N2O7S2Na (5)
molecular weight	604.67 (6); 580.66 (4)
background level	variable
detection limit (ppb)	0.15 (6); 0.061 (3); 0.007 (5)
max excitation wavelength (nm)	554
max emission wavelength (nm)	575
solubility	70 g/l (6)
sorption tendency	moderate (5); Kd=30-40 cm3/g (16)
photochemical instability	low (5)
effect of pH	stable between pH4 - pH10
environmental/health effects	LD50>10 g/kg (rat) (17,21); possibly mutagenic; LC50=450 mg/l (rainbow trout) (21)
commercial form	powder
manufacturer	Farbwerke Hoechst AG

Dye

tracer name	Sulforhodamine G
colour index	CI 45220; Acid Red 50
chemical formula	$C_{25}H_{27}N_2O_7S_2Na_2$ (5); $C_{29}H_{33}N_2O_7S_2Na$ (5)
molecular weight	631 (6); 608.71 (4)
background level	variable
detection limit (ppb)	0.02 (6); 0.005 (5)
max excitation wavelength (nm)	530
max emission wavelength (nm)	560
solubility	50 g/l (6)
sorption tendency	moderate (5); Kd= 0.9-2.0 cm3/g (7)
photochemical instability	low (5)
effect of pH	
environmental/health effects	LD50>10 g/kg (rat) (21)
commercial form	powder
manufacturer	Farbwerke Hoechst AG

tracer name	Tinopal CBS-X
colour index	CI Fluorescent Brightener 351
chemical formula	
molecular weight	
background level	variable
detection limit (ppb)	0.01 (5); 10 (13)
max excitation wavelength (nm)	355
max emission wavelength (nm)	435
solubility	0.1 g/l (13)
sorption tendency	medium (5)
photochemical instability	high (5,13)
effect of pH	
environmental/health effects	LD50=7.8 g/kg (17); 5.6 g/kg; non-carcinogenic, non-mutagenic; LC50=130-241 mg/l (21)
commercial form	
manufacturer	Ciba Geigy UK Ltd

tracer name	Uranine (Sodium Fluorescein)
colour index	CI 45350; Acid Yellow 73
chemical formula	$C_{20}H_{10}O_5Na_2$
molecular weight	376.28 (4)
background level	variable
detection limit (ppb)	0.002-0.01 (6); 0.29 (3); 0.002 (5); 0.01 (10); 0.02 (16)
max excitation wavelength (nm)	491
max emission wavelength (nm)	514
solubility	high (20); 25 g/l (6); 500 g/l @ 80°C (16)
sorption tendency	high (1); high below pH 6, low above pH 6 (20); low (16); very low (5); Kd=0.00-0.31; rd=1.25 (16); rd=10-39.3 (18); Kd=0 cm3/g (7)
photochemical instability	high (5); k=0.013 (15); k=0.030-0.032 (16)
effect of pH	fluorescence affected below pH6.5; max intensity >pH9
environmental/health effects	not toxic to goldfish or crucians (16); LD50=4.7 g/kg (mouse)(17,21), 6.7 g/kg (rat); non-carcinogenic, non-mutagenic; LC=1372-3433 mg/l (21)
commercial form	powder; aqueous solution
manufacturer	Brico Commercial Chemicals Co Ltd

Fluorocarbon

tracer name	
chemical formula	CBr_2F_2
boiling point	24.5
solubility in water	soluble
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

tracer name	
chemical formula	$CBrClF_2$
boiling point	-4.0
solubility in water	unknown
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

tracer name	
chemical formula	$CBrI-CBrF_2$
boiling point	47.3
solubility in water	unknown
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

tracer name	Freon-11
chemical formula	CCl_3F
boiling point	23.8
solubility in water	0.11 wt% @ 25°C
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

tracer name	Freon-113
chemical formula	$CCl_2F-CClF_2$
boiling point	47.4
solubility in water	0.017 wt% @ 25°C
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

tracer name	Freon-12
chemical formula	CCl_2F_2
boiling point	-29.8
solubility in water	0.028 wt% @ 25°C
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

tracer name	Freon-13
chemical formula	$CClF_3$
boiling point	-81.1
solubility in water	unknown
environmental effects	low biological hazard but acts as a greenhouse gas
analysis	electron capture detector/GC

Gas

tracer name	133 Xe
background ug/l	
solubility mg/l	
retardation	
use	
detection method	
detection limit ug/l	

tracer name	222 Rn
background ug/l	
solubility mg/l	
retardation	short half life (3.8 days); virtually absent in surface water which has reached equilibrium with the armosphere
use	detecting the location of diffuse groundwater entering surface water
detection method	
detection limit ug/l	

tracer name	85 Kr
background ug/l	
solubility mg/l	
retardation	
use	
detection method	
detection limit ug/l	

tracer name	Ar
background ug/l	570 (1)
solubility mg/l	60.6 @ 20°C
retardation	inert and unreactive, should not be retarded in saturated conditions
use	
detection method	
detection limit ug/l	

tracer name	CO
background ug/l	0.006 (1)
solubility mg/l	28 @ 20°C
retardation	
use	
detection method	
detection limit ug/l	

tracer name	He
background ug/l	0.0082 (1)
solubility mg/l	1.5 @ 20°C
retardation	little retardation wrt SEC in saturated media
use	not effective in unsaturated zone - partitions strongly in gas phase
detection method	vacuum dialysis & helium leak detector (4He only?)
detection limit ug/l	

Gas

tracer name	Kr (stable)
background ug/l	0.27 (1); 0.39-0.42 (22); 0.42-0.56, 1.08 (23)
solubility mg/l	234 @ 20°C
retardation	retarded by dissolving into air; may also sorb a small extent onto clay and organic material
use	not suitable for unsaturated zone as dissolves in air?
detection method	GC/MS
detection limit ug/l	

tracer name	Ne
background ug/l	0.17 (1)
solubility mg/l	9.5 @ 20°C
retardation	inert and unreactive, should not be retarded in saturated conditions
use	
detection method	
detection limit ug/l	

tracer name	NO
background ug/l	0.33 (1)
solubility mg/l	1100 @ 20°C
retardation	
use	
detection method	
detection limit ug/l	

tracer name	SF6
background ug/l	
solubility mg/l	37.5 @ 22°C (24)
retardation	may be retarded by organic carbon, but no evidence of retardation in sand with f(oc)=2.5 wt% (24)
use	detector of NAPL pools due to sorption to liquid organic phases
detection method	GC headspace
detection limit ug/l	5

tracer name	Xe (stable)
background ug/l	0.057 (1)
solubility mg/l	658 @ 20°C
retardation	may sorb a small extent onto clay and organic material
use	
detection method	
detection limit ug/l	

Ion

tracer name	ammonium
chemical formula	NH_4^+
background level	< 5 mg/l (1)
solubility	
sorption	high
analytical method	uv-visible spectrophotometry with chem procedures
detection limit	
diffusion coefficient	
interaction with aquifer	high loss to ion exchange
environmental/health effects	

tracer name	benzoate
chemical formula	
background level	low
solubility	
sorption	very low
analytical method	HPLC
detection limit	few ppb
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	borax
chemical formula	$Na_2B_4O_7.10H_2O$
background level	low
solubility	low; 16.2 g/l @ 10°C
sorption	low
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	bromide
chemical formula	Br^-
background level	low; <1 mg/l (1)
solubility	
sorption	low, but may undergo ion exchange in low pH conditions in the presence of clay
analytical method	specific ion electrode; spectrophotometry; n a; Dionex ion chromatograph
detection limit	0.5 ppm (specific ion electrode); 0.05 ppm (DIC) (23)
diffusion coefficient	1.76 x 10-5 cm2/s
interaction with aquifer	stable
environmental/health effects	

tracer name	chloride
chemical formula	Cl^-
background level	high (1)
solubility	
sorption	low, but may undergo ion exchange in low pH conditions in the presence of clay
analytical method	c f; mercuric thiosulphate method
detection limit	1 ppm
diffusion coefficient	1.71 x 10-5 cm2/s
interaction with aquifer	fairly conservative; weakly adsorbed by some soils
environmental/health effects	large quantities make water unpotable

tracer name	dichromate
chemical formula	$Cr_2O_7^-$
background level	
solubility	
sorption	
analytical method	AAS
detection limit	10 ug/l
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

Ion

tracer name	fluorobenzoates
chemical formula	
background level	
solubility	
sorption	
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	iodide
chemical formula	I^-
background level	very low; <0.01 mg/l (1); unstable (5)
solubility	
sorption	greater than Br or Cl
analytical method	various, including specific ion electrode (not v. accurate)
detection limit	
diffusion coefficient	
interaction with aquifer	affected by sorption and microbiological activity
environmental/health effects	

tracer name	lithium
chemical formula	Li^+
background level	low; 0.05-0.3 mg/l (1)
solubility	
sorption	high
analytical method	optical emission/absorption spectrometry
detection limit	absorption: 4-10 ug/l; emission: 0.004 ug/l
diffusion coefficient	
interaction with aquifer	high loss to ion exchange
environmental/health effects	

tracer name	lithium chloride
chemical formula	$LiCl$
background level	low
solubility	good; 637 g/l @ 0°C
sorption	low
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	lithuim bromide
chemical formula	$LiBr$
background level	
solubility	
sorption	
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	magnesium
chemical formula	Mg^{++}
background level	2-40 mg/l (1)
solubility	
sorption	medium
analytical method	spectrophotometry
detection limit	
diffusion coefficient	
interaction with aquifer	affected by sorption and ion exchange
environmental/health effects	

Ion

tracer name	potassium
chemical formula	K^+
background level	fairly low; 0.2-10 mg/l (1)
solubility	
sorption	high?
analytical method	flame emission; spectrophotometry
detection limit	
diffusion coefficient	
interaction with aquifer	affected by sorption and ion exchange
environmental/health effects	

tracer name	potassium chloride
chemical formula	KCl
background level	
solubility	347 g/l @ 20°C
sorption	
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	sodium chloride
chemical formula	$NaCl$
background level	high
solubility	357 g/l @ 0°C
sorption	
analytical method	conductivity meter; specific ion electrode; surface resistivity survey
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	strontium
chemical formula	Sr^{++}
background level	medium
solubility	
sorption	medium
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	sulphate
chemical formula	SO_4^-
background level	high
solubility	
sorption	low, but may undergo ion exchange in low pH conditions in the presence of clay
analytical method	turbidimetric
detection limit	
diffusion coefficient	
interaction with aquifer	
environmental/health effects	

tracer name	thiocyanate
chemical formula	SCN^-
background level	
solubility	
sorption	
analytical method	
detection limit	
diffusion coefficient	
interaction with aquifer	retarded relative to Br^- under aerobic conditions
environmental/health effects	

Microorganism

tracer name	Aerobacter aerogenose 243
size	150 Å
effective distance	680 m (27)
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	decays to 10% over 28 days (27)
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	BS3a
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	t½ = 613 hours @ 12°C (26)
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	f1
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	Ka = 1.34E-01 on 5g sand, 20°C
die-off rate	t½ = 126 hours @ 12°C (26)
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	PM6c
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	Ka = 4.20E-03 on 5g sand, 20°C
die-off rate	
time required for assay	
environmental effects	
cost	
comments	
examples of use	

Microorganism

tracer name	PM7a
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	t½ = 1195 hours @ 12°C (26)
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	T7
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	Ka = 1.06E-01 on 5g sand, 20°C
die-off rate	t½ = 1296 hours @ 12°C (26)
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	T4
size	
effective distance	1600 m (28)
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	VH5a
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	Ka = 4.33E-02 on 5g sand, 20°C
die-off rate	
time required for assay	
environmental effects	
cost	
comments	
examples of use	

Microorganism

tracer name	b: f2
size	
effective distance	
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	bacteria (general)
size	0.2-10 um
effective distance	
use	various; mostly used in two-well natural gradient tests
aquifer medium	
concentration needed	
background level	marker needed to distinguish tracer bacteria from background bacteria
detection method	recovered by filtration then incubated on agar
adsorption	
die-off rate	
time required for assay	1-2 days
environmental effects	some bacteria may be pathogenic
cost	relatively inexpensive
comments	
examples of use	

tracer name	bacteria: E.coli
size	
effective distance	920 m (12); 2.5 km (25)
use	various; indication of faecal pollution
aquifer medium	
concentration needed	
background level	not natural inhabitants of soil or groundwater
detection method	
adsorption	
die-off rate	
time required for assay	1-2 days
environmental effects	some strains may be pathogenic
cost	
comments	
examples of use	

tracer name	bacteriophage
size	0.2-1.0 um
effective distance	1600 m (25)
use	modelling the movement of microbial pathogens in groundwater; safer than viruses
aquifer medium	any; useful in media where flusorescent dyes are easily adsorbed
concentration needed	small (eg 5 x 10(10) per ml)
background level	
detection method	sampling and incubation
adsorption	adsorbed less than fluorescent tracers
die-off rate	
time required for assay	0.5-1 day
environmental effects	feed on specific bacteria; harmless to humans and animals
cost	
comments	
examples of use	

Microorganism

tracer name	Lycopodium spores
size	25-33
effective distance	
use	establishing flowpaths and approximating groundwater velocity
aquifer medium	karst
concentration needed	1 kg spores per 10000 gpm discharge per mile of travel
background level	should be analysed prior to testing; dying spores will distinguish them from those occurring naturally
detection method	plankton nets and microscope
adsorption	
die-off rate	
time required for assay	0.5
environmental effects	no known health effects
cost	higher than for dyes
comments	
examples of use	

tracer name	v: bovine Enterovirus
size	
effective distance	35 (30)
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	v:poliovirus
size	
effective distance	<40 m (29)
use	
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
die-off rate	
time required for assay	
environmental effects	
cost	
comments	
examples of use	

tracer name	viruses
size	0.2-0.8 um
effective distance	
use	modelling the movement of microbial pathogens in groundwater
aquifer medium	
concentration needed	small
background level	
detection method	sampling and incubation
adsorption	
die-off rate	
time required for assay	3-5 days
environmental effects	
cost	
comments	
examples of use	

Microorganism

tracer name	yeast
size	2-3 um
effective distance	> 7 m in 48 hours (11)
use	provides information about potential movement of bacteria
aquifer medium	
concentration needed	wide range
background level	negligible
detection method	filtered through membrane filters then incubated and colonies counted
adsorption	
die-off rate	
time required for assay	1-2 days
environmental effects	none
cost	cheap
comments	
examples of use	

Particle

tracer name	bacteria (general)
size	1-10 um
effective distance	
use	various; mostly used in two-well natural gradient tests
aquifer medium	
concentration needed	
background level	marker needed to distinguish tracer bacteria from background bacteria
detection method	recovered by filtration then incubated on agar
adsorption	may be filtered
environmental effects	some bacteria may be pathogenic
cost	relatively inexpensive
comments	

tracer name	bacteria: E.coli
size	
effective distance	920 m (12)
use	various; indication of faecal pollution
aquifer medium	
concentration needed	
background level	
detection method	
adsorption	
environmental effects	some strains may be pathogenic
cost	
comments	

tracer name	float
size	large
effective distance	
use	establishing flowpath; appproximating flow velocity
aquifer medium	karstic
concentration needed	minimal
background level	none
detection method	recovered by seiving water; counted manually
adsorption	none, but may get trapped due to large size
environmental effects	minimal
cost	cheap
comments	

tracer name	fluorescent polystyrene microspheres
size	0.05 to 90 um
effective distance	
use	investigation of particulate movement, eg pathogens, colloids; analysis of solid samples also possible (19)
aquifer medium	
concentration needed	
background level	
detection method	epifluorescence microscopy; spectrophotometry (19)
adsorption	
environmental effects	
cost	
comments	

Particle

tracer name	paper
size	large
effective distance	
use	establishing flowpath; appproximating flow velocity
aquifer medium	karstic
concentration needed	minimal
background level	none
detection method	recovered by seiving water; counted manually
adsorption	none, but may get trapped due to large size
environmental effects	minimal
cost	cheap
comments	

tracer name	signal-emitting float
size	large
effective distance	
use	karst tracing
aquifer medium	karstic
concentration needed	one
background level	none
detection method	location of explosion determined by seismic methods at surface; sound impulses detected by microphones
adsorption	none, but interference from other signals possible
environmental effects	minimal
cost	relatively expensive
comments	seldom used due to cost

tracer name	spores: lycopodium
size	30 um
effective distance	spores last well in polluted water but not in slow flow or water with high sediment concentration
use	
aquifer medium	most successful in karst; spores must be kept in suspension (a few miles/hr)
concentration needed	
background level	injected spores dyed to distinguish them from background
detection method	examined under microscope
adsorption	not adsorbed
environmental effects	no health threat
cost	
comments	

tracer name	viruses
size	0.2-1.0 um
effective distance	
use	modelling the movement of microbial pathogens in groundwater
aquifer medium	
concentration needed	small (eg 5 x 10 per ml)
background level	
detection method	
adsorption	
environmental effects	low health threat from animal enteric viruses; humam enteric viruses unsuitable due to disease potential
cost	
comments	

Particle

tracer name	yeast
size	2-3 um
effective distance	> 7 m in 48 hours (11)
use	provides information about potential movement of bacteria
aquifer medium	various
concentration needed	wide range
background level	negligible
detection method	filtered through membrane filters then incubated and colonies counted
adsorption	filtered but not adsorbed
environmental effects	none
cost	cheap
comments	

Radioisotope

tracer name	131I
half life	
source	
radiation types	gamma
particle energy (MeV)	0.36
detection method	
detection limit	
"age" range	
use	

tracer name	131I
half life	8 d
source	
radiation types	beta
particle energy (MeV)	0.61
detection method	measurement of beta emission
detection limit	high sensitivity
"age" range	
use	

tracer name	133Xe
half life	
source	
radiation types	gamma
particle energy (MeV)	0.08
detection method	
detection limit	
"age" range	
use	

tracer name	133Xe
half life	5.3 d
source	
radiation types	beta
particle energy (MeV)	0.35
detection method	
detection limit	
"age" range	
use	

tracer name	14C
half life	5730 y
source	natural cosmic radiation
radiation types	beta
particle energy (MeV)	0.156
detection method	tandem accelerator mass spectrometer
detection limit	
"age" range	500 - 30000 y
use	

tracer name	198Au
half life	2.7 d
source	
radiation types	beta
particle energy (MeV)	0.96
detection method	measurement of beta emission
detection limit	high sensitivity
"age" range	
use	direction of flow from a borehole; tracing of activated sludge - follows suspended particulate phase

tracer name	198Au
half life	
source	
radiation types	gamma
particle energy (MeV)	0.41
detection method	
detection limit	
"age" range	
use	

tracer name	222Rn
half life	3.8 d
source	decay of 238U in rocks
radiation types	alpha
particle energy (MeV)	5.49
detection method	
detection limit	
"age" range	
use	residence time of groundwater

tracer name	22Na
half life	2.6 y
source	
radiation types	
particle energy (MeV)	
detection method	
detection limit	
"age" range	
use	

tracer name	24Na
half life	15 h
source	
radiation types	beta
particle energy (MeV)	1.39
detection method	(in situ) NaI crystal scintillator
detection limit	
"age" range	
use	short duration experiments

Radioisotope

tracer name	24Na
half life	
source	
radiation types	gamma
particle energy (MeV)	1.4, 2.8
detection method	
detection limit	
"age" range	
use	

tracer name	32Si
half life	650 y
source	
radiation types	beta
particle energy (MeV)	0.21
detection method	
detection limit	
"age" range	
use	

tracer name	36Cl
half life	310000 y
source	
radiation types	beta
particle energy (MeV)	0.71
detection method	tandem accelerator mass spectrometer (very few laboratories have capablity for analysis
detection limit	
"age" range	5x10(4) - 2x10(6)
use	

tracer name	39Ar
half life	265 y
source	
radiation types	beta
particle energy (MeV)	0.57
detection method	
detection limit	
"age" range	100 - 1000
use	

tracer name	3H
half life	12.43 y
source	environmental (5-20TU); thermonuclear testing 1954-1966 (1000's TU)
radiation types	beta
particle energy (MeV)	0.018
detection method	liquid scintillation counting
detection limit	1 ppt
"age" range	groundwater pre-1953 <5 TU, groundwater post 1953 > 5 TU
use	rate of groundwater recharge over last c.40 years

tracer name	46Sc
half life	
source	
radiation types	gamma
particle energy (MeV)	0.89, 1.12
detection method	
detection limit	
"age" range	
use	

tracer name	46Sc
half life	83.8 d
source	
radiation types	beta
particle energy (MeV)	0.36
detection method	
detection limit	
"age" range	
use	adsorbed onto solids - used for tracing particulate matter

tracer name	82Br
half life	35.3 h
source	
radiation types	beta
particle energy (MeV)	0.44
detection method	(in situ) NaI crystal scintillator
detection limit	
"age" range	
use	

Radioisotope

tracer name	82Br
half life	
source	
radiation types	gamma
particle energy (MeV)	complex
detection method	
detection limit	
"age" range	
use	

tracer name	85Kr
half life	10.76 y
source	nuclear weapons testing and reprocessing fuel rods from nuclear reactors
radiation types	beta
particle energy (MeV)	0.67
detection method	low-level gas proportional counting
detection limit	
"age" range	c. 10 - 40 y
use	movement of groundwater recharge; inputs less erratic than 3H

tracer name	85Sr
half life	65 d
source	
radiation types	gamma
particle energy (MeV)	0.51
detection method	
detection limit	
"age" range	
use	

tracer name	EDTA-46Sc
half life	83.8 d
source	
radiation types	
particle energy (MeV)	
detection method	
detection limit	
"age" range	
use	non-adsorbed, used for tracing liquid eg leachate plumes

tracer name	EDTA-51Cr
half life	27.8 d
source	
radiation types	gamma
particle energy (MeV)	0.32
detection method	
detection limit	
"age" range	
use	studies of leachate plumes nad unsaturated zone moisture movement

tracer name	EDTA-60Co
half life	5.26 y
source	
radiation types	beta
particle energy (MeV)	0.32
detection method	
detection limit	
"age" range	
use	

tracer name	EDTA-60Co
half life	
source	
radiation types	gamma
particle energy (MeV)	1.33, 1.17
detection method	
detection limit	
"age" range	
use	

Stable Isotope

tracer name	13C
source	environmental
use	determining origin of groundwater
sampling method	glass bottles with vapour-proof caps, stored in the dark
analysis	mass spectrometry

tracer name	14/15N
source	environmental
use	determining origin of nitrogen/nitrate
sampling method	glass bottles with vapour-proof caps, stored in the dark
analysis	mass spectrometry

tracer name	18O
source	environmental
use	recharge area; groundwater residence time; differentiation of geological horizons
sampling method	glass bottles with vapour-proof caps, stored in the dark
analysis	mass spectrometry

tracer name	2H
source	environmental
use	recharge area; groundwater residence time; differentiation of geological horizons; deuteriated organic compounds used to trace hydrocarbon movement, degradation and retardation
sampling method	glass bottles with vapour-proof caps, stored in the dark
analysis	mass spectrometry

tracer name	32/34/36S
source	environmental
use	determining origin of sulphate
sampling method	glass bottles with vapour-proof caps, stored in the dark
analysis	mass spectrometry

Water temperature

tracer type	Water temperature
analysis	temperature probe (in situ)
use	small-scale tests