INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

GROUNDWATER IN IRELAND
~
25TH ANNIVERSARY CONFERENCE

PROCEEDINGS

OF THE

IAH (IRISH GROUP)

25th ANNUAL GROUNDWATER CONFERENCE

Tullamore Court Hotel, Co. Offaly

Tuesday 19th and Wednesday 20th April 2005

2005 IAH (Irish Group) Tullamore Seminar Organising Committee:

President: David Ball, Consultant, Dublin.
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Conference Sub-Committee: Michael Gill, Komex, Dublin; Coran Kelly, Natalya Hunter Williams, Geological Survey of Ireland, Dublin.

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INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS

IRISH GROUP

Groundwater in Ireland

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TULLAMORE COURT HOTEL
TULLAMORE
Co. OFFALY

Tuesday 19th & Wednesday 20th April, 2005

The IAH (Irish Group) are grateful to the Geological Survey of Ireland for providing assistance with the registration aspects of the conference

International Association of Hydrogeologists (Irish Group)

The International Association of Hydrogeologists (IAH) was founded in 1956 to promote co-operation amongst hydrogeologists, to advance the science of hydrogeology world wide, and to facilitate the international exchange of information on groundwater. The IAH is a worldwide scientific and educational organisation with more than 3,500 members in 135 countries.

The Irish Group of the IAH was started in 1976 and has over 130 members. It hosts a well attended, annual groundwater conference in the Irish Midlands, and holds technical discussion meetings on the first Tuesday of every month between October and June, in the Geological Survey of Ireland in Dublin. The following members are serving on the 2005 IAH (Irish Group) Committee:

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Michael Gill, Komex	☎(01) 824 5000

CONFERENCE OBJECTIVE

The study, understanding, use and public perception of groundwater has changed considerably in the last 25 years. This year's conference acknowledges these changes, however the principal objective is to focus on the present and future. The conference addresses how the fundamentals of groundwater science and our current knowledge, can be combined with recent research and new and emerging technologies to progressively advance our understanding of the groundwater environment in Ireland.

The main objectives of the conference are to:

- assess what we have learned in the past quarter century, and determine what we still need to know;
- update hydrogeologists, engineers, planners, environ-mental scientists on local and international groundwater practice; and,
- provide an outline of the current issues relating to groundwater, to determine what future issues may be, and to highlight how legislation and research will shape our future.

To achieve these objectives a broad range of experienced speakers have been brought together to present ideas and results. Topics range from large scale climate change, reduction in recharge and the realisation that current large abstraction rates may not be sustainable in the future, to the small scale identification of viruses deep in groundwater below leaking urban sewers and hence, potentially, rural septic tanks.

Bringing the groundwater community up to date, and alerting and informing those involved in groundwater related studies of new ideas and techniques, will help us improve how we work and establish a platform from which we can build for the future.

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Groundwater in Ireland
25th Anniversary Conference

PROGRAMME DAY I - TUESDAY, 19th APRIL

10:00 Registration
Tea, Coffee, & Exhibits

10:50 Welcome and Introduction
Bob Aldwell, (past President) and
David Ball, (current President) IAH (Irish Group)

SESSION I : Groundwater in Ireland – Present State of Knowledge – three perspectives

11:00 Perspective 1 - The State and Research Institution Perspective – "Groundwater in Ireland – Hydrology with Attitude"
Paul Johnston, Lecturer, Trinity College Dublin

11:30 Perspective 2 - Groundwater Consultant's Perspective "Professional Hydrogeologists - A lot done - more to do."
Teri Hayes, Manager, White Young Green Ireland

12:00 Perspective 3 – External Perspective - "Rock type versus Fractures" – current understanding of Irish Aquifers
Vincent Fitzsimons, Hydrogeologist, presently in Scottish Environmental Protection Agency, and previously with Geological Survey of Ireland (GSI).

12:30 Panel Discussion

12.45 Buffet Lunch & Exhibits

SESSION II: New and Outstanding Issues

14:00 Hydrogeology in Ireland in 2005: "There is more, but is it better" - comparison of classical techniques and analysis, with recent developments
Eugene Daly, Eugene Daly Associates

14:20 Fracture flow and preferential groundwater flow paths in hard rocks. Illustrations from Precambrian and lower Palaeozoic strata in Wales
Nick Robins, British Geological Survey.

14:40 The Tydavnet aquifer in Co Monaghan: The only bedrock aquifer in Ireland under significant stress from pumping?
Bruce Misstear (TCD), Les Brown (TCD) and Taly Hunter-Williams (GSI).

15:00 Changing precipitation scenarios: Preliminary implications for groundwater flow systems and planning
John Sweeney, NUI Maynooth

15:20 Panel Discussion

15:40 Tea, Coffee & Exhibits

SESSION III: New Tools and Practical Examples I

16:10 Modern groundwater equipment – examples of use and results in pumping tests, monitoring salt-water intrusion and dynamics of karst limestone 'plumbing' systems.
Michael Gill (Komex), David Ball, Patrick Laffly (TMS Environment Ltd.)

16:30 Lapps Quay Development, Cork.- A case study in de-watering and instrumentation
Gary Holmes, WJ Groundwater Ltd., UK

16:50 Latest techniques in tracing the movement of water through limestone aquifers
David Drew, Trinity College Dublin

17:10 A new approach for analysing test pumping data in heterogeneous aquifers – implications for quarrying
Paul Younger, Newcastle University

17:30 Panel Discussion. (Close at 17:45)

The panel discussion will be followed by a wine reception in the Tullamore Court Hotel sponsored by City Analysts Ltd.

PROGRAMME DAY 2 - WEDNESDAY, 20th APRIL

SESSION IV: New Tools and Practical Examples II

09.00 Advances in forensic identification of petroleum related releases into the environment using source specific markers
Ken Scally, ALcontrol Geochem

09.20 Groundwater and current public health issues
Eileen Loughman, Eastern Health Board / Kildare County Council

09:40 Quantifying and understanding the extent of microbiological pollution in urban groundwater systems
Aidan Cronin, Robens Institute, University of Surrey

10:00 Advances in geophysics – time lapse resistivity imaging – location and movement of landfill plumes
Paul Gibson, NUI Maynooth.

10:20 Evaluating the impacts of groundwater abstraction on surface water features
Michael Streetly, Environmental Simulation International

10:40 Panel Discussion

10:55 Coffee, Tea and Exhibits

SESSION V: River Basin Developments

11:15 River Basin Districts – Overview of scope and results from all components of the work
Grace Glasgow, Kirk McClure Morton

11:35 Physical characterisation and risk characterisation of river basin districts: groundwater aspects
Donal Daly, Geological Survey of Ireland.

11:55 Groundwater monitoring for implementation of the Water Framework Directive; initial results and assessment
Sean Moran & Gerry Baker, O'Callaghan Moran Assoc.

12:15 River Basin Districts - The Future - monitoring, classification and programme of measures
Pat Duggan, Department of Environment and Local Government

12:30 Panel Discussion

12.50 Closing Address
Patrick Laffly, TMS Environment Ltd

13:00 Buffet Lunch

14:30 Golf Outing sponsored by ALcontrol Geochem

Table of Contents

THE ORIGINS OF THE IAH ANNUAL SEMINAR

Geoff Wright, Geological Survey of Ireland

As the Annual Seminar reaches its Silver Jubilee, you may be interested to hear how it began, in the pre-Celtic Tiger year of 1981.

Ireland's first IAH member was the late David Burdon, who was in fact one of the original founder members of the International Association in 1952. Our second member was Bob Aldwell, happily still with us, who was recruited by David Burdon in 1974. When I and David Ede joined GSI in late 1975, David, Bob, and Eugene Daly called a meeting of 10 or so prospective members in GSI in December of that year, and an Irish Branch of IAH was formed. David and Bob became the inaugural President and Secretary, respectively, and Paddy Nicholson of Johnson Wellscreens, as Treasurer, made up the three-man committee.

In those early years our membership was, shall we say, compact, and our programme generally comprised about three discussion meetings and one field trip each year. The undoubted highlight of those early years was an international conference held in TCD in September 1979, followed by a 3-day field trip through Kilkenny, Waterford and Cork.

In 1980 the committee personnel changed: David remained as President, but I took over as Secretary and Kevin Cullen as Treasurer, and we considered how the branch could make progress. It was my view that we needed to expand our 'congregation' – to reach out to the wider community of engineers, well-drillers and environmental specialists who, if only for part of the time, were involved with groundwater. And one issue on my mind was the need to improve the way gravel aquifers were investigated and developed.

Meanwhile, in 1979, Atlas Copco had organised a very successful day-and-a-half meeting at the Limerick Inn, primarily to introduce the then revolutionary 'ODEX' system for rotary drilling in unconsolidated deposits. In addition to the ODEX presentations (which included drilling holes beside the hotel car park), a number of other good speakers had made presentations on Down-the-Hole Hammer drilling, and on drilling fluids, and the attendance had comprised a good mixture of practising drillers, engineers, and a sprinkling of hydrogeologists. That meeting, organised largely by Atlas Copco's local agent, Douglas Gordon (who has rarely missed an Annual Seminar in some capacity) was an eye-opener for me and proved that such a gathering, with an attractive theme, could succeed.

I tried to get Atlas Copco to repeat the exercise the following year with a presentation on Gravel Aquifer Development, but without success, so my thoughts turned to organising a meeting under IAH auspices. Kevin was keen to pursue the idea, and came up with the ideal venue – the Montague Hotel near Portlaoise, where he had recently supervised the drilling of a borehole in a local gravel aquifer.

So Kevin and I put a programme together (see Appendix) which followed the development of a gravel aquifer, beginning with geological/hydrogeological exploration, geophysical surveys (Eugene Daly and I having previously done a resistivity survey along the edge of the car park), through test drilling, well design and well screen selection, development, etc. For our main guest speakers I found the late Lewis Clark of the Water Research Centre (a former colleague in England) while Kevin recruited Bill Jungmann of Johnson Wellscreens, and also persuaded Dunnes Welldrilling (Mallow) to put on a drilling demonstration beside the car park.

The registration fee was a modest (even then) £20. We insured ourselves against financial shortfalls by borrowing much of the equipment (projectors, screens, etc.) from GSI, and using GSI's postal facilities (with the full support of our Director, Dr Cyril Williams). The IAH Group's profits from the 1979 conference also gave us a safety margin. The 'proceedings' were very slim, it must be said, so printing costs were low. We got excellent support from Johnson Wellscreens, from Minerex and from Dunnes Welldrilling.

Until quite late, we had no idea whether we would get 20, 50, or 100 attendees. In the event, we had about 120, and we reckoned the meeting so successful on all fronts that we should repeat it the next year, this time on Limestone Aquifers. The rest, as they say, is history.

Why 'seminar' rather than 'course' or 'conference'? Well, that was my choice. Although a 'seminar' is usually a smaller scale, perhaps half-day, meeting with only one or two speakers, the term conveyed something I wanted to emphasise: the meeting would have a definite aim of imparting information on one or two main themes: less formal than a course, but not as open-ended as a conference. Speakers were carefully selected to speak on particular topics in support of the selected theme. This approach has substantially persisted to the present, and I hope will continue.

In 1983 we moved from the Montague to the Killeshin Hotel in Portlaoise, and we changed from a winter date (the well-drillers' quiet season) to the spring. We stayed at the Killeshin until overcrowding caused us to move to our present Tullamore venue in 2001. That was also the year when the Foot-and Mouth outbreak caused us to cancel our traditional spring date and hold the seminar in October.

As the IAH membership grew and our programme expanded, it became essential to appoint an additional committee member to look after the annual seminar - the first being Stephen Peel in 1984. More recently, an ad hoc sub-committee has spread the load more widely.

One important difference between now and 1981 is that our IAH Group membership has increased about tenfold, so that it makes up a much greater proportion of our annual attendance. But still the majority of our audience comes from outside the IAH, so it is still our principal 'outreach' event of the year. Our UK visitors often remark that it has no parallel on the other side of the Irish Sea.

Another change over the years has been that the programme has become fuller, with more speakers, but less time for each to speak (and the titles of talks have become longer!). Audio-visual aids have, of course, changed from colour slides and acetates to the almost universal adoption of Powerpoint projection, and the volume of Proceedings has become much more professional – the committee no longer has to spend the Monday evening collating and binding in the meeting room!

Here's to the next 25!

Geoff Wright,
GSI Groundwater Section

The Appendix to these Proceedings lists the themes and presentations at every seminar since 1981.

Session I

Groundwater in Ireland – Present State of Knowledge – three perspectives

Perspective 1: Paul Johnston

Page 1

GROUNDWATER CONSULTANT'S PERSPECTIVE "PROFESSIONAL HYDROGEOLOGISTS, A LOT DONE – A LOT MORE TO DO."

Teri Hayes P.Geo., Director, White Young Green

ABSTRACT

The day to day professional working life of a consultant hydrogeologist has changed significantly over the last twenty years. Firstly, increased legislation has encouraged more work in all areas of the environment. The implications of Environmental Impact Assessment (EIA) legislation, the Water Framework Directive and the proposed Liability Directive are discussed. Secondly, growth in technology has significantly altered data collection, analysis and reporting. The absence of any long-term groundwater records and incorrect use of models are reviewed. Finally, the impact of the "Celtic Tiger" on the Irish economy has resulted in substantial increase in work for Irish hydrogeologists. Trends in Infrastructure growth, developments on contaminated land, waste and water development are summarised.

All of these factors have increased the pace and type of work currently being undertaken. Hydrogeologists have begun to specialise, especially in the area of contaminated land, resulting in a loss of available skills in other less active areas such as groundwater development. The proliferation of reports and the lack of adequate numbers of qualified regulators have led to inadequate reviewing of reports and poor standards in places, particularly EISs. Increased guidelines, the requirement for "qualified persons" by regulators and increased peer review should counter this in the future. New opportunities are arising due to issues such as the move to risk assessment analysis and increased concentration on implications for biodiversity.

1.0 INTRODUCTION

Much has changed for Irish hydrogeologists from the early seventies to the present day. This paper presents my personal opinion on the major issues which have resulted in changes in the day to day working life of a consultant hydrogeologist. These issues are technological advances, increase in environmental legislation and the impact of the Celtic Tiger on Ireland's economy.

2.0 EFFECT OF GROWTH IN ENVIRONMENTAL LEGISLATION

The quantum of legislation relating to the water environment has grown significantly over the last twenty years. Environmental Impact Assessment did not even exist within our legislation or planning process until the introduction of the Environmental Impact Directive in 1985 (85/337/EEC). This increase in legislation has led to work in almost all areas; impact assessment, water supply development, waste management, remediation, site management etc. Some relevant pieces of legislation are discussed below with regard to their implications for hydrogeology related work.

2.1 ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

The legal requirement for Environmental Impact Studies (EIS) has led to a lot of work on the ground. However, the quality of work completed has not always been of a high standard. Many EIA managers feel that the soils and water section of an EIS can be completed without the professional expertise of hydrogeologists or do not provide adequate funds for this component of the EIS. Unfortunately, these inadequacies are not regularly picked up by regulators. In 2002, the IGI prepared comprehensive guidelines on the requirements to be included within the soil and water section of an EIS (Geology in EIS – A Guide, 2002). This guideline document compliments the EPA guideline document (Guidelines on the Information to be included in an EIS, 2002). Adherence to these guidelines together with increased peer review through processes such as oral hearings etc should improve the content of EIAs.

Cost is always an issue with EISs, the developer is obviously more interested in spending his money on bricks and mortar than reports. The engineering consultant who often heads up the EIS will often look at the EIS as a profit loss exercise to win the more profitable design and build contract. The hydrogeologist has to argue the necessity of their proposed work programme. However, we now need to be even more cautious in planning our EIS. How many of us can, hand on heart state that their soils and geology aspect of a windfarm development would have included adequate mitigation for a mud slide as occurred in East Galway recently. To ensure against any professional indemnity claims, EISs in the future are likely to include more comprehensive risk assessment analysis. The new requirements for Strategic Environmental Assessment (SEA) will continue to expand this area of work into the future.

2.2 WATER FRAMEWORK DIRECTIVE

The Water Framework Directive (2000/60/EC) will establish River Basin Districts in which River Basin Management will be implemented. This Directive incorporates most previous legislation regarding water quality and quantity.

The Republic of Ireland has been divided into River Basin Districts for the purposes of managing these projects. Local authorities have hired consultants to work with themselves and the other regulators over the next four years. In excess of €60 million is to be spent over the next four years on this project (River Basin District Management Systems – Technical Requirements for Groundwater and Related aspects, 2001). Suitable monitoring locations and parameters will be identified and management measures proposed for improving or maintaining good water quality. This programme will set up catchment management organisations with agreed programmes of work and goals. For those not involved in the development of river basin management plan, on-going local work is likely to be required to implement the measures identified within the plans. One of the difficulties in developing river basin management plans will again be the lack of baseline data, particularly in relation to the habitat requirements of wetlands. Although significant work has been undertaken in the mapping and identification of protected species and habitats (under the Habitat Directive 92/43/EEC), little work has been undertaken with regard to habitat and species requirements in terms of hydrology and hydrogeology. On-going research at Pollardstown Fen on behalf of Kildare County Council with regard to assessing the requirements of the *Vertigo Geyeri* snail species (Annex 1 species under the Habitat Directive) show how difficult this research can be. The studies to date (over a period of more than three years**)** have identified that the species requires a particular level of substrate saturation which is dependent on humidity, recharge and rate of upwelling groundwater. On-going monitoring will be required to confirm and modify these findings. These types of studies are extremely costly due to the intensive monitoring requirements and require a lengthy number of years of monitoring and analysis.

2.3 THE LIABILITY DIRECTIVE

Selling and purchasing of sites together with assessing oil and chemical leaks continue to provide significant work for hydrogeologists working in the area of contaminated land. Liability for contaminated land has not been established in Irish law unlike in the UK, which has a Contaminated Land Act. However, a number of existing Acts fuel this type of work. These include the Water Pollution Act 1977 and 1990, the EPA Act 1992, the Public Health Act 1878, and the Safety, Health and Welfare at Work Act 1989.

A recent prosecution of the local Managing Director of Texaco and two corporate officers in Belgium will reinforce people's fears about inadequate environmental management of their sites. A petrol station was supplied by Texaco but operated under lease by a third party. After a petrol leak due to defective petroleum storage facilities, hydrocarbon migrated into adjoining properties. Texaco suspended operations at the station and undertook remedial works. However, the Belgian authorities prosecuted Texaco Belgium, its managing director (Monsieur Van de Walle) and two other company officers on criminal charges under the Belgian interpretation of the EU waste directives. This case turned contamination into a crime and treated leaked petroleum and contaminated soil as an illegal moving of hazardous waste.

The introduction of the Liability Directive (2004/25/CE), which is expected to come into Irish legislation in 2007 is likely to ensure on-going work for hydrogeologists in the growing area of contaminated land investigation. The Directive will establish in law the principle that the "polluter pays" for damage to soil groundwater and biodiversity. The directive covers all instances of liability post 1997. It allows a neighbour etc to prosecute an operator whose operation has caused or has potential to cause damage to off site land, water, endangered species and natural habitats.

3.0 EFFECT OF TECHNOLOGICAL ADVANCES

Over the last 20 years, scientists have moved from the use of cumbersome, slow mainframe computers to the modern PC. This has facilitated greater manipulation, analysis and modelling of data at the hydrogeologist's desk. In addition the data logger has almost replaced the water level dipper as a hydrogeologists tool. However, as with any scientific advances there are always a few downsides as well as upsides. Two of these are summarised below.

3.1 ABSENCE OF LONGTERM GROUNDWATER DATABASE

Firstly, unlike surface water, there is no available long-term data bank of groundwater levels or quality in Ireland. As part of the EPA Act 1992, the EPA is obliged to develop and maintain a hydrometric programme. Currently this database stands at approximately 250 monitoring points distributed over the Island. Water levels are monitored biannually (high water table and low water table) as well as collecting basic water quality information. Longer term records are available for a small number of these boreholes where data was derived from other sources such as the GSI. However, in general the length of record is short or incomplete. The absence of a long-term water level record for comparison can make interpretation difficult, resulting in a dependence on modelled data rather than a more indisputable comparison with reality. An example of this is where lower peak winter and summer water levels have been measured within the Kildare aquifer over the last few years. It is difficult to conclude how much of this effect is due to recent weather patterns resulting in lower than normal recharge to the aquifer. Statistical modelling (time series analysis) of meteorological data and the available six years of water level monitoring data has been utilised to estimate "natural" water levels within the aquifer. However, the absence of a long-term water level record means that there is no comprehensive dataset for model calibration.

Obviously, as time goes on this database will become more useful. In addition the increase in regional projects (such as River Basin Management Plans as required under the Water Framework Directive) and regulatory requirements (monitoring requirements of IPC and landfills) will add to the density within the database.

3.2 INCORRECT USE OF MODELLING

Another disadvantage of technological advances is that many clients now expect a model for everything. Off the shelf modelling packages are readily available and are being used indiscriminately. The main difficulty arises when models are used in a "black box" approach without being modified to suit site specific conditions or having their limitations clearly outlined. Inappropriate input parameters are often used to fit the existing scenario by mathematicians who do not have an understanding of the range of values that are suitable. In the past the hydrogeologist had to derive a conceptual model, present it to the reader and draw conclusions. Many regulators/readers may not be familiar with the limitations of specific models. A conclusion derived from a model, and outlined in a weighty report with lots of mathematical jargon can add a semblance of credibility. Hydrogeologists need to be intrinsically involved in the design, use and presentation of modelled data. Over the last 10 years a breed of specialists called "*modellers*" have appeared. Many "modellers" are experts at fitting square pegs in round holes. There are many situations where insufficient baseline data exists to construct a model to reflect the existing environment let alone to be used to make predictions on the effects of the activities of a proposed development. Hydrogeologists will now need to either become modellers, or work closely with modellers if we are to stay at the forefront of our own science.

4.0 THE EFFECT OF THE CELTIC TIGER

Ireland's growth into a Celtic Tiger economy has insured that more hydrogeologists are working in Ireland than ever before. Those working in the 1970s could not have imagined the amount of hydrogeology related projects on-going at present or in fact the rate of speed at which clients expect projects to be completed in. To cater for this increase in workload the number of people working in hydrogeology/environmental geology has increased significantly. In a recent industry survey by the IGI, the numbers employed in hydrogeology and environmental geology greatly outweighed other areas of employment.

As there does not appear to be any significant slowing down in the economy this area of employment is likely to continue to grow.

4.1 INFRASTRUCTURE GROWTH

Roads and housing have been major areas of development and work for hydrogeologists in recent years. In February 2005, the Minister for Transport, Martin Cullen T.D announced Government investment of €1.415 billion for National Roads infrastructure in 2005. This funding will allow for the completion of eight major road projects and the commencement of construction on 19 roads this year. This compares with €294 million spent in 1997 (NRA Website).

More than 83,000 new homes were built in Ireland in 2004, bringing to 440,000 the number of new homes built since 1997. In 2003 63,000 were built and *c*.40, 000 were built in 2002 (Irish Construction Overview, 2005). This compares with approximately 10,000 in 1990.

Landfills were an issue in the 1970s and continue to be so, in order to meet the needs of our consumer society. The biggest change with in relation to waste disposal to ground has been the decrease in the number of operating landfills. "*Waste Management - Changing our Way"* (1998) stated an aim to reduce the number of operating landfills from 120 to 20. Currently Ireland has approximately 35 operating landfills. The introduction of the Waste Management Act 1996 (S.I. No. 10 of 1996) and Landfill Directive 1999 ((1999/31/EC) has lead to an exponential growth in monitoring requirements and monitoring costs for active landfills. Older closed landfills appear to have been left in a "limbo" situation and are likely to be a source of future work in terms of remedial measures and management. There has been a major change in the acceptable design of landfill sites, "Dilute and Disperse" is no longer an option and the design criteria are based around sealed cells that should not leak.

Although the Waste Management Act and Landfill Directive had not been implemented in the seventies, good quality work was undertaken with regard to assessing environmental impact of new landfills. Today's increased quantum of site assessment work is often as much required to mitigate for "attack" at the omnipresent oral hearing as much as for protecting the environment.

4.2 TRENDS IN CONTAMINATED LAND DEVELOPMENTS

No area of hydrogeology has incurred as much growth as the area of contaminated land. In fact, many hydrogeologists have no experience working outside of this area. A measure of the degree of increase in this type of work can be seen by the significant increase in the quantity of contaminated soil being exported from the country. In 2003, 218,521 tonnes of contaminated soil was exported compared with 23,691 tonnes in 1998 (National Waste Database, 1998 and 2003). A recent study for 2004 undertaken by White Young Green Ireland in the greater Dublin region showed an increase of 39% on the 2003 figure. In the past the work consisted primarily of managing "dig and dump". Increase in waste costs and expertise in alternative remedial methods and risk management have altered the nature of this work significantly. There is an on-going movement towards assessment and management of sites using site specific risk assessment rather than comparison with specific soil and water quality standards, many of which had little scientific basis.

4.3 TRENDS IN GROUND WATER DEVELOPMENT

Increased growth in many urban areas has led to pressure on existing water supplies. Approximately 75% of drinking water in Ireland is abstracted from surface water (National Development Plan 2000-2006). Engineers have always been more comfortable with surface water sources for public supply, but as available resources have become rare, increased emphasis on new sources including groundwater is occurring. Public water supplies are now generally part of a regional development plan. As such the resource assessment and evaluation is on a regional and catchment basis rather than single site developments as in the past. This will lead to increased knowledge of our available groundwater resource in Ireland. Unfortunately as many hydrogeologists have not evaluated a pump test since their Masters studies, the industry is losing the sort of "hands on" experience that the David Burdons of this world were steeped in.

Difficulties also arise in developing groundwater resources due to poor public perception of groundwater quality and difficulties in assessing environmental impact of water developments on wetlands. Increased reporting by the EPA on drinking water supplies nationwide has highlighted the relative poor quality of group water schemes (many of which are groundwater sourced). The government has recognised this by committing €644 million in the National Development Plan to the improvement of these schemes. The 2001 report for the monitoring period 1998-2000 stated that there was no widespread pollution of aquifers and that elevated faecal coliform counts in many counties indicate the need for disinfection and for better controls over the siting of water supplies. Unfortunately, this faecal coliform data is often reported without explanation within the press, fuelling a lack of confidence in groundwater sources. No comparison is given with surface water supplies where faecal coliform counts greatly exceed those generally encountered in groundwater.

There has been a slight move to development of groundwater supplies by industry. This is likely to be a more active area once more significant charging of water is brought in by local authorities. Also there is a growing need for private water supplies where development growth is moving ahead of infrastructure provision.

5.0 CONCLUSIONS

The work of the consultant hydrogeologists has changed significantly since the early seventies in terms of the pace and type of work being undertaken. Due to the quantum of work, hydrogeologists have begun to specialise in certain areas, in particular contaminated land. This specialisation is beneficial to the areas where work exists at present but may be detrimental to the quality of future work in areas such as groundwater resource evaluation. Hydrogeologists who work solely in the area of contaminated land will not gain sufficient field experience to develop an adequate instinctive feel for other areas of hydrogeology such as water yields, impact assessment or wetland management. Similarly, with the dependence on computer packages and routine comparisons with industry standards, the hands-on hydrogeologist with a feel for what to expect and a knowledge of "ballpark" figures has become a bit of a dinosaur in the age of the Celtic Tiger.

The rapidly developing economy has generated a proliferation of work resulting in a proliferation of reports for review by our regulators and planning departments. Unfortunately there are not enough adequately qualified professionals to ensure standards in quality are maintained. The introduction of professionalism in geologists through the IGI, the increasing requirement for a "suitably qualified" person to complete technical reports and improved guidelines should encourage good quality work and reporting. The increase in oral hearings should also act as a catalyst to this due to peer review.

New opportunities are also expected particularly through the Liability Directive and the Water Framework Directive. Much of the legislation requires assessment of the impact on biodiversity. The expertise of hydrogeologists is bound to be required for this type of work. Continuous training and inclusion of new research data and techniques is required to ensure that consultant hydrogeologists are well placed to take up any new opportunities.

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"ROCK TYPE VERSUS FRACTURES" – CURRENT UNDERSTANDING OF IRISH AQUIFERS

Vincent Fitzsimons, Scottish Environmental Protection Agency
Donal Daly, Groundwater Section, Geological Survey of Ireland
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ABSTRACT

All bedrock types in Ireland are aquifers, and all have the potential for high permeabilities in particular localities. As such, the concept of a "poorly permeable aquifer" is not appropriate to Ireland, and may not be appropriate in other countries with significant fractured rock resources. Instead emphasis is placed on transmissivity/productivity and the extent of flow systems that can occur in different aquifers.

1.0 INTRODUCTION

1.1 OBJECTIVE

The bedrock aquifer classification system for the Republic of Ireland has been developed by the Geological Survey of Ireland. The fundamentals of this system are in place (e.g. DELG/EPA/GSI, 1999 and Wright, 2000) and the classification process as been underway over the past two decades. However the EU Water Framework Directive has recently driven an increase in the pace of classification as well as some new developments in the conceptualisation of flow. A draft of the national bedrock aquifer map is now complete.[1]

This paper describes the basis for the bedrock aquifer classification scheme, focussing on some key elements of the conceptualisation of flow within different aquifer types.

1.2 SCOPE

The classification scheme has been developed primarily using geological assumptions. These assumptions have been tested using data, where available, on lithology and geological structures, spring flows, well yields, specific capacities, karst features, drainage density, and river baseflow. Though the quality of individual data points is sometimes poor, the data are usually sufficient to classify aquifers at a regional scale on the basis of the overall weight of evidence. Classification cannot be made on the basis of individual data points.

The classification provides information suitable for regional-scale assessments of groundwater resource potential and risks to those resources from contaminant and abstraction pressures. Unless accompanied by site-specific ground investigation data, the aquifer classification is not suitable for identifying optimum sites for groundwater abstractions, nor is it suitable for assessing specific contamination issues at specific sites.

[1] *http://193.178.1.182/website/gwps_multi/viewer.htm*

2.0 HYDROGEOLOGICAL CHARACTERISTICS OF IRISH AQUIFERS

2.1 PERMEABILITY

- Fissure permeability is considered dominant in the bedrock aquifers of the Republic of Ireland.
- Any well drilled at any site in any bedrock aquifer in Ireland can encounter high fissure permeabilities. At this scale, permeabilities are influenced by local factors and the distribution of permeability between sites or across a single site can appear random.
- On a more regional scale, the development of fissure permeability is not random. In Irish bedrock aquifers, it is considered to be a function primarily of lithology and structural history (refer to Table 1).

Table 1 Summary of Geological Influences on Fissure Permeability

Factor	Scenarios leading to higher fissure permeability
Degree and openness of fracturing	Higher frequencies of more open fractures generally results in higher fissure permeability. This can occur where there is one or more of the following: • A higher intensity of stress; e.g. south Munster • More competent and brittle rock; e.g. coarse grained limestones and sandstones • More recent stress, when the current aquifers were buried to shallower depths and subject to subsequent brittle deformation; e.g. Tertiary stresses (Dunphy, 2004) • An extensional stress orientation; e.g. north-south jointing in south Munster, and reactivation of north west – south east faults due to Tertiary stresses (Dunphy, 2004). • Thinner bedding • Proximity to the top of the rock; generally there are more fractures and wider apertures closer to the rock surface (e.g. Heath and Durrance, 1985).
Fine, insoluble material in the bedrock	As a result of infilling by clay, the presence of major fractures does not necessarily result in high flows (Banks et al., 1992). Lower proportions of fine and insoluble material usually results in higher fissure permeability; fractures in pure limestones and sandstones will be less likely to infill with fine grained material.
Dolomitisation	Increased dolomitisation will usually give higher fissure permeability. Increased dolomitisation is often localised and can occur preferentially where there are: • Large faults • Purer limestones
Karstification	Increased karstification gives higher fissure permeability. Karstification is often localised and often preferentially occurs: • In pure limestones • Close to the water table • Close to fracture zones and bedding planes. • Where groundwater is actively being recharged • Where recharge waters are more acidic

2.2 TRANSMISSIVITY

In assessing the resource potential of fractured rock, the concept of transmissivity is more useful than that of permeability. Transmissivity is a function of the permeability multiplied by the saturated thickness of an aquifer. The concept of transmissivity can be difficult to apply to fissured bedrock. For example, all the water being transmitted to a well might be coming from one open fissure, 0.1m in width. For the purposes of aquifer classification, it would be meaningless to consider the transmissivity of individual fissures. However, there is some validity in considering larger scale bulk transmissivity, averaged across larger thicknesses of rock and larger areas of ground.

The issue of aquifer thickness is problematic in Irish bedrock aquifers because fissure permeability generally reduces with depth below the water table and depth below the top of the rock. As a consequence, the aquifer thickness in many situations is much less than the mapped thickness of the geological unit. In concept, fissure permeability is considered to vary across three broad zones. These are described briefly below:

i) *Broken and weathered rock zone*. This usually extends to within 1m to 2m of the top of the rock. Moving upwards across the zone, there is often a gradual transition from rock to subsoil. In rocks with a lower content of impurities, the zone often has a similar appearance to gravel, or very gravelly till.

ii) *Zone of more interconnected fissures*. This zone usually extends from the base of the broken and weathered zone to depths of up to 30m. When drilling below the water table, this zone is characterised by regular strikes of groundwater. Permeability is usually developed from open joints, bedding planes and faults. Higher rates of weathering and karstification usually occur closer to the top of rock and/or closer to the water table. The lower limit of this zone is therefore taken as the lowest summer water level (in un-pumped conditions) which would normally be expected in the various rock types. Based on the limited number of hydrographs currently available to the GSI, this lower limit is normally expected to be within 30m of the top of rock in pure/dolomitic limestones and within 15m of the top of rock in most other rock types. Obviously, many exceptions occur, and this zone can be absent in certain areas, and much deeper than 30m in large fault zones. An example of the latter was encountered at the Thomastown public groundwater supply in County Kilkenny, where drilling through sandstones encountered regular strikes of groundwater to depths of over 60m (Buckley and Fitzsimons, 2002).

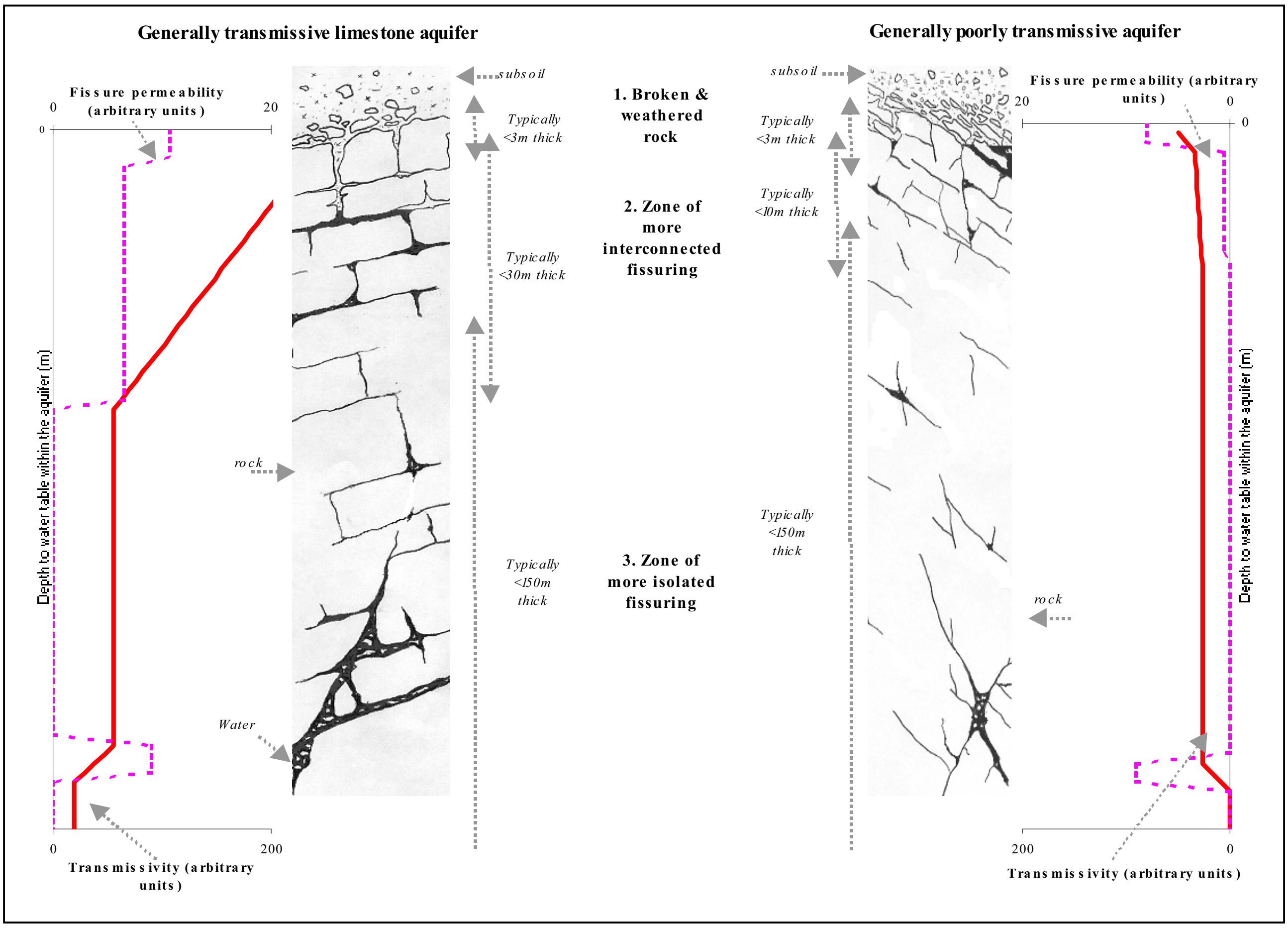
iii) *Zone of more isolated fissures*. This zone usually extends downwards from the base of the broken and weathered zone. Permeability is developed primarily by faulting. As with the zone above, the permeability of individual fractures and the degree of interconnection will generally be higher in pure/dolomitic limestones and sandstones. However, very large faults with very high permeabilities can occur in any rock type. Jointing will often become less frequent and less open moving deeper through the zone. Therefore, fault zones will often be hydraulically isolated from one another. Even when drilling below the water table, the intervals between these fault zones can appear completely dry. The water level in a well can drop very sharply if these fault zones are dewatered when pumping. Production wells in Ireland have rarely exceeded 120m in depth and most information for the deeper parts of this zone has been derived from the deep zinc/lead mines in the limestones of the Irish Midlands. Some very large inflows of water have been encountered at depth in these mines, but these strikes do not occur below 150m at Lisheen, for example (Fault Analysis Group, University College Dublin, personal communication, 2003).

   The presence of warm springs in certain parts of Ireland - for example in the Calp limestone of north-east Kildare and south-west Meath where temperatures of 13°-25°C have been found - indicates that some groundwater circulation can occur from depths of over several hundred metres (Burdon, 1983). However, the occurrence of warm springs is rare, and most groundwaters are 9°-11°C. This suggests that upwelling from deep warm groundwaters generally occurs in insignificant quantities compared to the amounts of cooler groundwater which are circulating at shallower depths. Until more information becomes available, therefore, it is assumed that deep circulation is not a significant factor in most aquifers and that the effective lower limit of this zone is usually less than 150m. Exceptions comprise the main dolomitic aquifers, where significant flows are expected below 200m, and some of the more brittle sandstone formations where they are confined by lower transmissivity rocks above (e.g. the Westphalian sandstones and the Kiltorcan-type sandstones).

Figure 1 provides a schematic of the interaction between fissure permeability, saturated thickness and transmissivity in hypothetical transmissive and poorly transmissive aquifers. Key points to highlight are:

- Even though overall transmissivity may be very different, the fissure permeabilities in the top few metres of most aquifers can be quite similar. When generalising over a large portion of an aquifer, the main reason for the greater transmissivity in important aquifers is the depth to which relatively frequent and significant strikes of water can be expected to occur.
- Though fissure permeabilities can be high, the effective aquifer thickness can be quite limited, even in the important aquifers. This means that transmissivities (when generalising over a large portion of an aquifer) are often relatively low compared to important aquifers world-wide.
- Transmissivity often does not decrease linearly with depth (refer to **Figure** 1). At lower water levels, the rate of water level decline (in summer months or during excessive well pumping) can therefore be unexpectedly rapid. As such, aquifers with a generally lower transmissivity are often best exploited using more than one well to try to limit the drawdown in each well.

Figure 1 Conceptual variation of transmissivity and fissure permeability with depth in two hypothetical aquifers



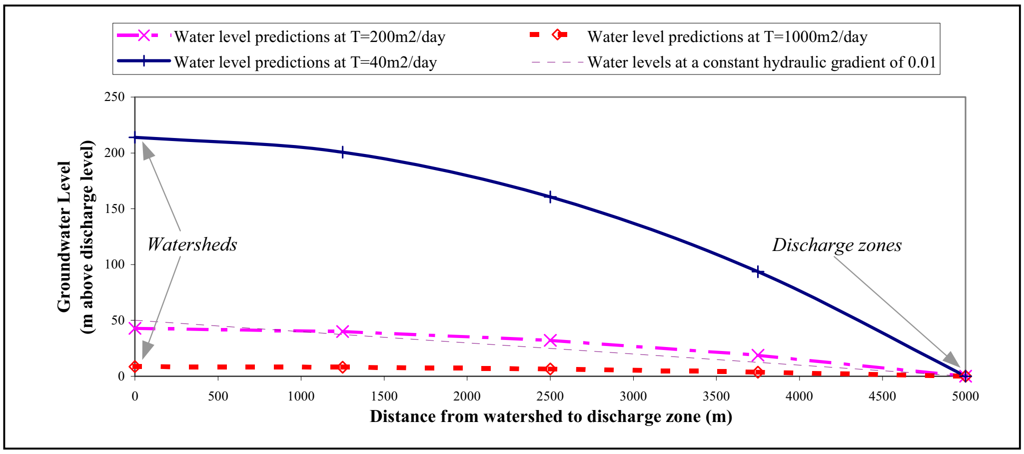
Given the limited availability of transmissivity data in Irish aquifers, the concept of productivity has been developed as a simplified proxy. One value of productivity per well can be calculated from a knowledge of pumping rate and specific capacity (Wright, 2000).

2.3 FLOW AND FLOW PATHS

The overall transmissivity of an aquifer has a key influence on the length to which groundwater flow paths can potentially extend. This, in turn has a key influence on the extent to which impacts can spread across aquifers.

Figure 2 depicts the water table gradient in three hypothetical aquifers encompassing the range of transmissivity typical in Ireland. Average annual conditions are assumed and storage is therefore not considered. Darcy's law is assumed to be applicable and each aquifer is assumed to be horizontal with a uniform transmissivity.

Figure 2 Relationship between water level and transmissivity along a simulated groundwater flow line of 5 km length and 1m width receiving a constant recharge of 250 mm/year



Even at a moderate recharge rate of 250 mm/year, it is clear from Figure 2 that the low transmissivity aquifer cannot manage the amount of water involved. A range in head of over 200 m along a single flow system does not occur in Ireland, and hydraulic gradients in excess of 0.01 are rare. Even the moderate transmissivity aquifer exceeds this gradient in places along the flow line. In reality, both the moderate and low transmissivity aquifers in this example would become 'full', and would develop zones of discharge to surface water (i.e. springs), over a much shorter distance from a groundwater divide than 5 km.

This phenomenon is evident on any topographic map: aquifers are often sub-divided by surface water discharge features into a large number of separate flow systems. An examination of areas of similar topography and subsoil suggests that most parts of Ireland are rarely more than 10 km upslope of surface water, and, in some areas, this distance reduces to less than 1 km. This variation in drainage density can partly be explained by variations in aquifer properties and recharge. In Figure 3 the previous simulations have been adjusted such that the gradient along each flow line cannot exceed 0.01. Where a gradient in excess of 0.01 is predicted, the model boundaries are adjusted such that a new discharge zone is added. Results suggest that the low transmissivity aquifers will generally be unable to support flow systems of more than a few hundred *metres* in length, while higher transmissivity aquifers will generally be able to support systems of a few *kilometres* in length.

Figure 3 Relationship between water level and transmissivity, where the recharge is 250 mm/year and the hydraulic gradient is limited to a maximum of 0.01

Figure 3a Single flow system from gw divide to discharge zone

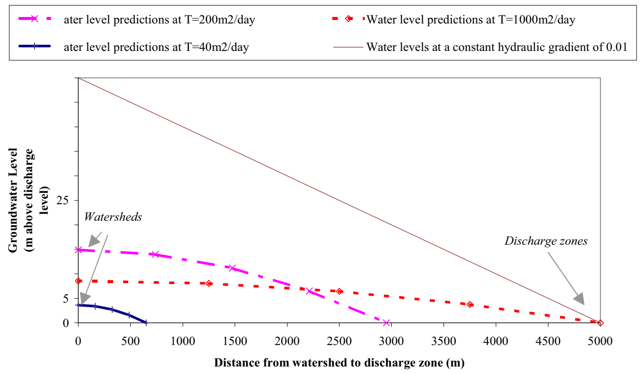
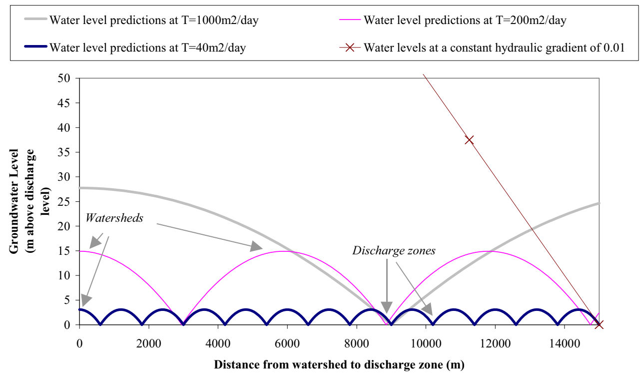


Figure 3b Multiple flow systems across each aquifer



2.4 FLOW AND FLOW VOLUMES

Theoretically, flow paths comprise a series of lines across which no flow occurs. In this context, the width of a flow path has no meaning and the extrapolation of flow volumes from the length and width of a flow path also has no meaning. However, at a large scale, flow systems can be considered to have a width as well as length. Examples of lateral dispersion and convergence of flows can be seen in contaminant plumes (becoming wider downgradient) and spring catchment areas (becoming narrower closer to the spring).

In the less important aquifers, high transmissivity zones will usually coincide with faults, where greater depths of fracturing occur. However, the transmissive fracture zones will not generally be more than a few tens or hundreds of metres in width. When it is considered that the faults themselves are usually several hundred metres or even a few kilometres apart, it is clear that most of these highly transmissive zones will be hydraulically quite isolated from each other. Taking a 3 km fault with a continuous zone of enhanced fissuring of 300m width, the largest average annual flows that the zone can support at a recharge rate of 250 mm/year will be around 600 m^3/day. The largest known sustainable yield from individual wells in the poorly transmissive aquifers is slightly over 500 m^3/day. This figure is broadly similar to those quoted for the largest wells and springs on Anglesey (Robins and McKenzie, 2005).

The more generally transmissive aquifers will also have highly transmissive fault zones separated by lower transmissivity ground. The key conceptual difference is that the intervening ground will have generally much deeper interconnected fissuring and generally much higher transmissivity than those in the generally poorly transmissive aquifers. This allows the highly transmissive zones to draw water from much wider intervals. Many of the source protection zones drawn around the large public supply springs in Ireland are over two kilometres in both width *and* length and the flows in over 50 of these springs nation-wide exceed 2,000 m^3/day. The Galmoy and Lisheen mines both lie within transmissive aquifers and both need to pump well over 10,000 m^3/day to keep the workings dry.

In summary, the more important Irish bedrock aquifers will have greater flow volumes within individual flow systems. These greater flows are due to the development of interconnected fissuring at greater depths *and* across wider areas. The less important bedrock aquifers can often have highly permeable zones and will occasionally have transmissive zones where interconnected fissuring occurs at greater depths, but these zones will not be sufficiently connected areally to allow significant groundwater flow volumes within individual flow systems.

The presence of large spring flows and high baseflows in rivers are therefore a key indicator of an aquifer's importance.

3.0 NATIONAL AQUIFER CLASSIFICATION ISSUES

3.1 INTRODUCTION

The aquifer categories defined in *Groundwater Protection Schemes* (DELG/EPA/GSI, 1999) are intended to describe both flow type and resource potential. They are as follows:

Regionally Important (R) Aquifers
- Karstified bedrock (**Rk**)
- Fissured bedrock (**Rf**)
- Extensive sand & gravel **(Rg)**

Locally Important (L) Aquifers
- Sand & gravel (**Lg**)
- Bedrock which is Generally Moderately Productive (**Lm** and **Lk**)
- Bedrock which is Moderately Productive only in Local Zones (**Ll**)

Poor (P) Aquifers
- Bedrock which is Generally Unproductive except for Local Zones (**Pl**)
- Bedrock which is Generally Unproductive (**Pu**)

In order to assist in the understanding and development of regionally important (**R**) limestone aquifers, the broad range of karst regimes has been compartmentalised into three categories. Where karstification is slight, the limestones are similar to fissured rocks and are classed as **Rf**, although some karst features may occur. Aquifers in which karst features are more significant are classed as **Rk**. Within the range represented by **Rk**, two sub-types are distinguished, termed **Rk**^{c} and **Rk**^{d}.

- **Rk**^{c} are those aquifers in which the degree of karstification limits the potential to develop groundwater. They have a high 'flashy' groundwater throughput, but a large proportion of flow is concentrated in conduits, numerical modelling using conventional programs is not usually applicable, well yields are variable with a high proportion having low or minimal yields, large springs are present, storage is low, locating areas of high permeability is difficult and therefore groundwater development using bored wells can be problematical.

- **Rk**^{d} aquifers are those in which flow is more diffuse, storage is higher, there are many high yielding wells, and development of bored wells is less difficult. These areas also have caves and large springs, but the springs have a more regular flow.

The aquifer categories can be grouped as follows:

- Karstic (Rk and Lk) aquifers;
- Gravel (Rg and Lg) aquifers;
- Productive fractured bedrock (Rf and Lm) aquifers;
- Poorly productive bedrock (Ll, Pl and Pu) aquifers.

This grouping is based on similarities in a) hydrogeological properties; b) resource value; c) likely monitoring requirements; d) influence on surface water characterisation; and e) the likely measures required to manage the groundwater. They can be considered as general groundwater types.

3.2 SUMMARY OF KEY AQUIFER CHARACTERISTICS

The classification scheme has been devised to provide conceptual information on the following characteristics:

- The length of flow path and scale of the flow systems which can develop.

- Contaminant fate and transport characteristics.
- The ability to support significant wetland ecosystems
- The potential for developing regionally significant groundwater supply sources.

Table 2 Conceptual differences between the aquifer categories

Scale of flow system	Aquifer Category	Potential for contaminant attenuation within the aquifer	Potential for supporting the most significant wetland ecosystems	Potential for obtaining individual well yields in excess of 400 m^3/day
Regional-scale: Flow paths potentially several kilometres in length. Flow volumes of tens of thousands of cubic metres per day.	**Rk c**	Very limited	Yes	Limited
	Rk d	Very limited	Yes	Yes
	Rf	Limited	Yes	Yes
	Rg	Yes	Yes	Yes
	Lm	Limited	Yes	Yes
Local-scale: Flow paths rarely exceed several hundred metres in length. Flow volumes of hundreds to thousands of cubic metres per day.	**Lg**	Yes	Yes	Yes
	Lk	Very limited	Limited	Some
	Ll	Limited	Limited	Some
	Pl	Limited	Very limited	Very limited
	Pu	Limited	None	None

The relationship between these characteristics and the aquifer categories is summarised in Table 2. Of these characteristics, the key element used in defining the aquifer categories is the scale at which flow systems can develop. This is the main criterion which separates a 'regionally important' aquifer from a 'locally important' or 'poor' aquifer and is closely related to the potential for supporting significant river and wetland ecosystems. The scale of the flow system is closely related to the scale at which impacts will occur. Damage to the water quality of a locally important aquifer could affect only those receptors within a few hundred metres of a hazard, but the same pressure could affect receptors several kilometres away in a regionally important aquifer. As described in Section 2, the scale at which flow systems can develop is closely related to the overall depth of interconnected fissuring and to the overall transmissivity within an aquifer. Though discrete, highly transmissive zones can occur across the whole range of aquifer types, the transmissivity will be higher across wider areas in the regionally important aquifers. This will result in a generally greater potential to transport larger volumes of groundwater across longer flow paths.

Note from Table 2 that the yield potential of an aquifer does not have a simple relationship to the potential size of a flow system. Many of the larger and more karstified aquifers, for example, will have regional-scale flow systems but obtaining large yields in these aquifers can be very difficult.

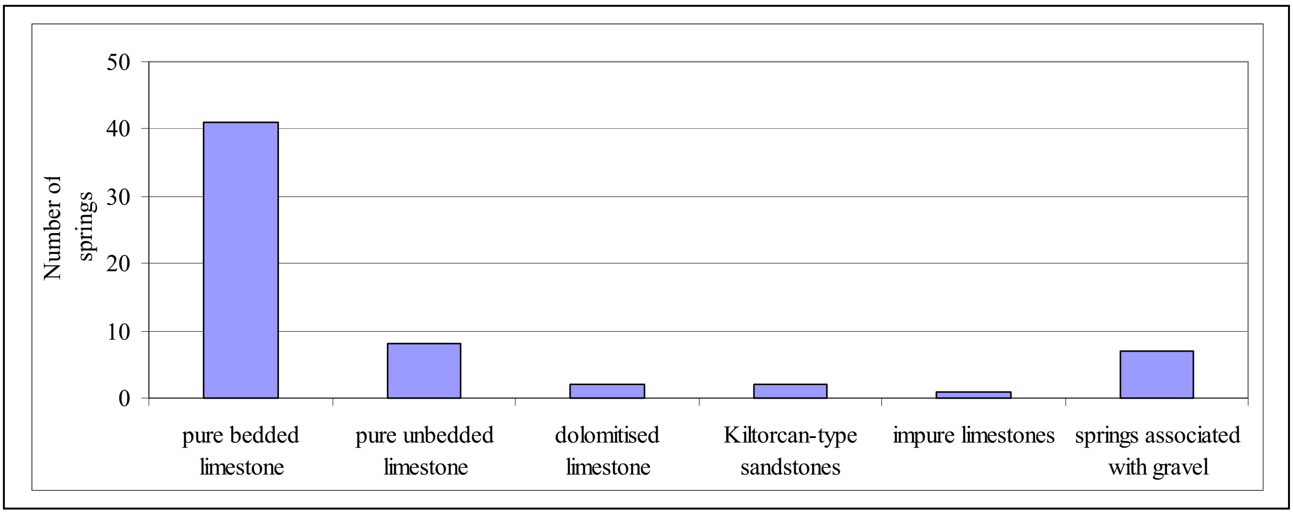
The potential for contaminant attenuation within the aquifer is closely related to the permeability type. The sand & gravel aquifers with predominantly intergranular flow will have a much greater potential for contaminant attenuation than the bedrock aquifers. In the bedrock aquifers, the potential will generally be limited to dilution and to those contaminants which degrade over time (e.g. certain bacteria).

3.3 CRITERIA FOR DELINEATING AQUIFER BOUNDARIES

In bedrock aquifers, regional-scale variations in the key properties will be dictated primarily by lithology and the fracture characteristics. The aquifer boundaries have been generally based, therefore, on mapped bedrock lithological units and regional fracture geology patterns. From first principles, the pure or dolomitic limestones would be expected to comprise Rk, Rf or Lm aquifers; the impure limestones would be expected to comprise Lm, or Ll aquifers; sandstones and volcanics would be expected to comprise Rf, Lm, or Ll aquifers; shales would be expected to comprise Pl or Pu aquifers and the remaining rock types would be expected to comprise Ll, Pl, or Pu aquifers. The position of individual aquifers within the ranges dictated by lithology would be expected to depend primarily on fracture characteristics. Some validation of these concepts can be provided through an examination of the distribution of large springs.

As discussed in Section 2, large, or high flowing springs represent regional-scale flow systems of the kind described in Table 2. They are defined as those where flow exceeds 2000 m^3/day (according to available data). In typical recharge conditions of 100 to 300 mm/year, average flows of this magnitude would require a recharge catchment area of between 2 km^2 and 7 km^2. Figure 4 depicts the known large springs in the country in relation to the bedrock type underlying each recharge catchment area. The main point to note is that 95% of these springs occur in pure limestone, dolomitised limestone or gravel. Only one spring occurs in impure limestone and none is associated with granites, shales, quartzites or any other lithology that occurs in Ireland

Figure 4. The relationship between known large springs and lithology



This distribution helps validate the close link that is believed to occur between lithology and aquifer category in many areas. Rocks such as granite and impure limestone are occasionally capable of providing well yields of a few hundred cubic metres per day along certain fracture zones where the depth of fissuring and transmissivity has been locally increased. However, these fracture zones will not generally be extensive enough to allow the development or regional flow systems. In a hypothetical example, if the fracture zone was 200m wide and the recharge 100 mm/year, the recharge catchment for a large spring would need to extend along this fracture zone for a distance of over 36 km. Continuously permeable fracture zones of this magnitude are rare in Ireland, helping to explain why large springs have not been found in rocks such as granite.

3.4 BEDROCK AQUIFER CLASSIFICATION

Based on the concepts described in this paper, the Geological Survey of Ireland has developed a national bedrock map specifically for the aquifer classification process. The process can be simplified into the following steps:

1) The bedrock geology was simplified into 27 lithologically and stratigraphically similar units (refer to Figure 5).
2) In parallel, a structural zonation map of the Republic of Ireland was developed (Dunphy, 2004). This map provides broad structural characteristics at a regional scale for 17 zones (refer to Figure 5). These characteristics include fault orientation and the orientation of extension / compression.

3) The structural and lithological maps were combined to provide the basic boundaries for aquifer classification.
4) Available lithological and hydrogeological data were compiled to assess the most appropriate category for each aquifer. Aquifer categories are summarised in Figure 6.

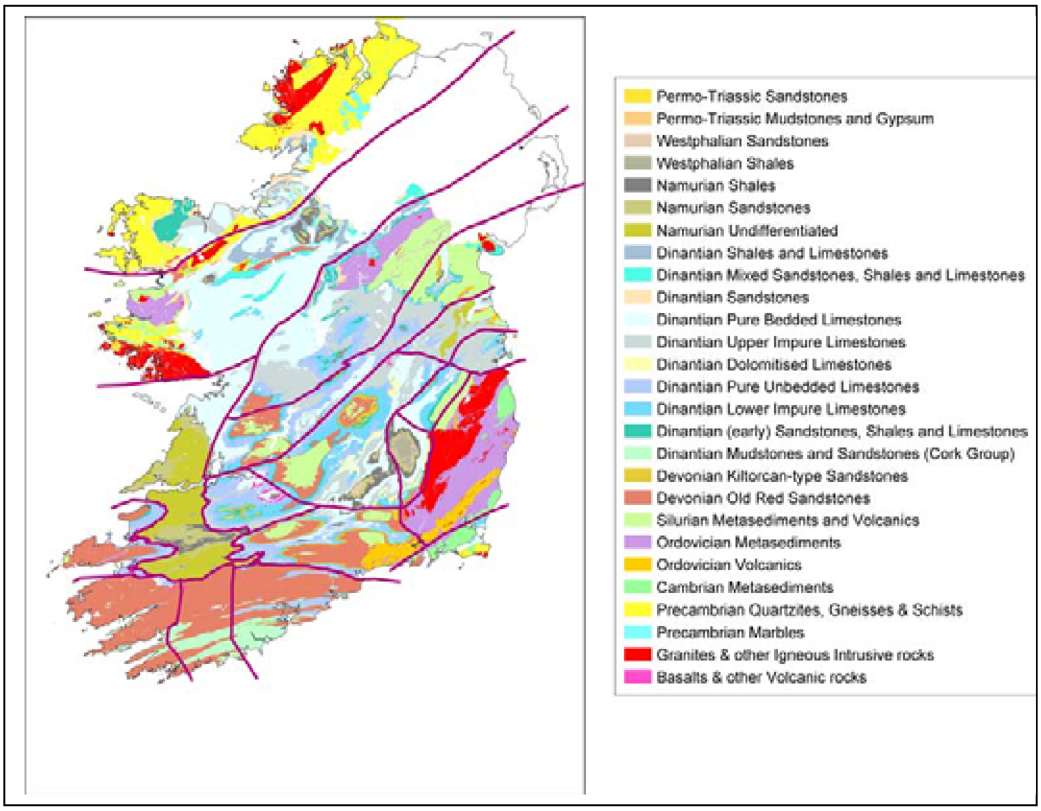


Figure 5: National bedrock map, simplified into lithologically and stratigraphically similar units. The boundaries of the national structural zones (Dunphy, 2004) have been superimposed.

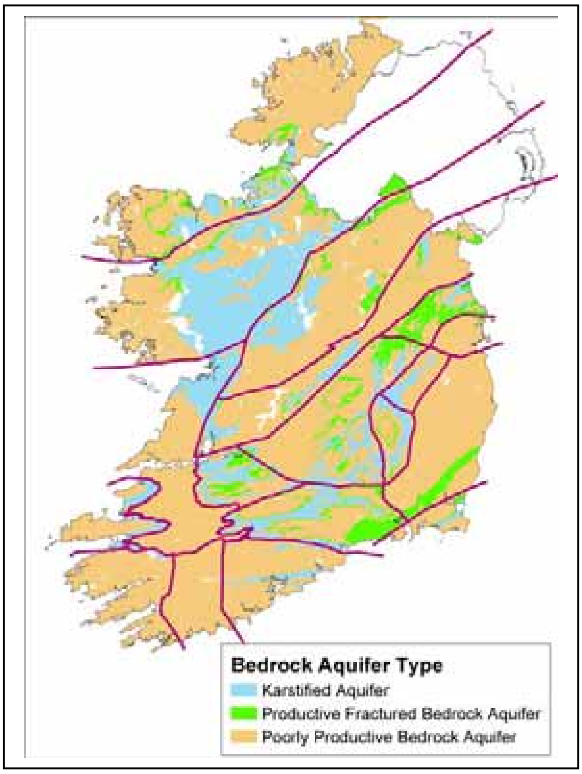


Figure 6: National bedrock aquifer classification, simplified into three broad groupings. The boundaries of the national structural zones (Dunphy, 2004) have been superimposed.

4.0 SUMMARY

Groundwater flow is very variable in Irish bedrock aquifers.

- Even the most productive aquifers in Ireland can have wells which yield no water.
- Fracture zones can occur in any rock type in Ireland. As such, excellent well yields can be obtained in even the least transmissive aquifers.
- All bedrock units are considered to have some groundwater resource potential. Bedrock 'non aquifers' do not occur in Ireland.

Permeabilities can be elevated in localised zones within even the poorest aquifers. The concept of poorly permeable aquifers is therefore not appropriate. Transmissivity, or its proxy "productivity" are more appropriate terms to use, as they encapsulate the variation in fissure permeability with depth. In bedrock aquifers, higher transmissivity and productivity values are generally due to greater depths of interconnected fissuring.

While permeabilities and well yields are variable across all aquifer types, flow volumes and the length of flow path are less variable. The more important Irish bedrock aquifers will have greater flow volumes within individual flow systems. These greater flows are due to the development of interconnected fissuring at greater depths *and* across wider areas. The less important bedrock aquifers can often have highly permeable zones and will occasionally have transmissive zones where interconnected fissuring occurs at greater depths, but these zones will not be sufficiently connected areally to allow significant groundwater flow volumes within individual flow systems. Regionally important aquifers can be considered to represent those where flow paths can potentially extend to several kilometres in length. In these aquifers, impacts from abstraction and contamination pressures are therefore more likely to extend to more distant and more significant receptors over wider areas.

5.0 CONCLUSIONS

Water supply in bedrock aquifers in the Republic of Ireland comes from fractures: essentially "holes" in the rock mass. To those well drillers and hydrogeologists working on a site-specific scale, these fractures can appear randomly distributed. However, this is not the case at a more regional scale, where the distribution is related to a combination of lithology and structural history. The most important aquifers in Ireland are those where there is a combination of soluble material and a structural history that incorporates geologically recent tensional stresses. The aquifers are characterised primarily by the occurrence of large springs, but also by a number of other factors including a higher frequency of productive wells. Consideration of aquifers at the regional scale is not academic; it is vital for effective planning of regional water supply schemes and for assessments of risks to groundwater receptors. More important aquifers will have greater flow volumes within individual systems and impacts from abstraction and contamination pressures are therefore more likely to extend to more distant and more significant receptors over wider areas.

All bedrock types in Ireland are aquifers, and all have the potential for high permeabilities in particular localities. As such, the concept of "poorly permeable aquifer" is not appropriate to Ireland, and may not be appropriate in other countries with significant fractured rock resources. Instead emphasis is placed on transmissivity/productivity and the extent of flow systems that can occur in different aquifers.

6.0 ACKNOWLEDGEMENTS

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SESSION II

New and Outstanding Issues

HYDROGEOLOGY IN IRELAND IN 2005: "THERE IS MORE, BUT IS IT BETTER"

Eugene Daly, Eugene Daly Associates

EXTENDED ABSTRACT

Although the study of hydrology can be traced back to the 17th century, the systematic study of groundwater did not begin until the early part of the 20th century. By the 1960s an accepted number of standard or classical scientific methods and field techniques had been developed for groundwater investigations.

Systematic groundwater investigation did not begin in Ireland until the late 1960s and early 1970s.

Many of the standard methods where developed in the United States where the aquifers are on a grand scale. In contrast in Ireland the principal aquifers are very restricted in area, with the bulk of groundwater movement occurring in the outcrop/subcrop areas, at shallow depths, relatively rapidly along short flow paths before discharging into springs or the normally effluent streams situated within these aquifers.

Owing to the particular hydraulic regime over most of Ireland, a considerable amount of information, over relatively small areas, is generally required to understand the nuances of the flow regime in study areas.

For the purposes of this lecture the standard methods and techniques have been grouped into six fields which are discussed below.

Hydrogeologists working in Ireland have always been fortunate in that the entire island was mapped on a 6" scale in the mid 19th century. However, the hydrogeology of the much of the limestones was a bit of a mystery until a modern interpretation of the stratigraphy was worked out in the 1970s and early 1980s. This stratigraphic interpretation was subsequently formalised by the Geological Survey in its 100,000 series of bedrock maps.

Owing to the complexity of the geology, the thick Quaternary (subsoil) cover and the absence of adequately described borehole logs in many areas, the available geological interpretation is often found to be insufficient for a detailed understanding of the flow regime in study areas.

The surface geophysical techniques now available are often of considerable assistance in filling in some of the gaps in our knowledge.

In the 1970s and for much the 1980s in Ireland boreholes were rarely drilled as an aid to hydrogeological investigation. Furthermore, the design, construction, testing and supervision of water wells were generally inadequate. However, since the middle to late 1980s the standard of water well drilling has improved significantly.

Most of the drilling work now being undertaken for hydrogeological or site characterisation is being done by companies specialising in site investigation for engineering projects. However, well completion is often inadequate for hydrogeological characterisation.

The well is the hydrogeologists laboratory, a window on the subsurface and our primary insight into the underground. Wells have become expensive. It is essential that the standard of design, construction and logging is consistent with the purpose for which they are being used. This is rarely achieved without experienced supervision.

In Ireland in the early days, there was a certain amount of emphasis on the quantitative side of surface water hydrology with little work on the qualitative side. Over the past thirty years this situation has changed completely. However, one is rarely of much use without the other

The same applies to groundwater in that the concepts of vulnerability and protection are a little meaningless without a similar level of knowledge of throughput.

Without observation wells the analysis of pumping test data is very limited especially in situations where the geology changes within the radius of influence of the well being tested. This type of setting is very common in Ireland and therefore in the 1970s and 1980s values for the aquifer characteristics, insights into hydraulic and boundary conditions where estimates at best.

We now have more observation/monitoring wells and a better, but still far from complete, insight into the hydrogeology of the sites we are looking at, however the level of analysis is often oversimplified. The standard techniques, the simple semi-log and log-log methods, are frequently unable to handle fracture systems with horizontal and vertical barriers within the radius of influence of the well.

Now that there are more observation/monitoring wells available, the potential exists for the use of slug (rising and falling head) tests to obtain more values for permeability. We are however inclined to use the simple or off-the-shelf methods of analysis. There are analytical methods for almost every hydraulic situation. However, the standard of borehole completion must be consistent with the sophistication of the analytical method employed.

The generally short flow paths in Irish Aquifers probably, often less than 5km, would not be expected to have a more than relatively simple chemistry. Whereas this is generally the case, there are often deviations from the norm over very short distances and in relatively small areas. The most typical situation is the development of ion-exchange, the replacement of calcium with sodium which signals the on-set of confined conditions. Groundwater reports currently being produced often omit even a very basic level of hydrochemical analysis.

Hydrogeologists now bathe in volumes of data from specifically designed and relatively expensive investigations. The level of mental application applied to this data is not always what it should be. The analysis of many investigations appears to stop short of the optimal use of the data and a more comprehensive understanding of the hydrogeological regime being examined.

To be concluded.

FRACTURE FLOW AND PREFERENTIAL GROUNDWATER FLOW PATHS IN HARD ROCKS – ILLUSTRATIONS FROM PRECAMBRIAN AND LOWER PALAEOZOIC STRATA IN WALES

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ABSTRACT

Groundwater in the Lower Palaeozoic and Precambrian hard rocks is mainly constrained to limited storage and circulation in an upper weathered and fractured zone. Some deeper circulation via favourable fractures is possible and there may be hydraulic connection with storage in Quaternary gravels and with surface waters. Examples from Wales illustrate some of the features typical of the small aquifer units that occur in these hard rocks and provide some of the methodologies that have been attempted in understanding groundwater recharge, storage and transport on a catchment scale.

1.0 INTRODUCTION

Groundwater is generally abundant in most areas of basement rocks (Lower Palaeozoic and older) despite the perception that these strata are supposed to be dry. Yields are generally small, typically only about 1 to 3 $l\ s^{-1}$, and baseline quality is good, as the waters are young and weakly mineralised, but vulnerability to pollution is generally high, although the pollution risk may be small in some upland areas. The stratigraphical sequence in Wales extends from the Precambrian through to recent deposits and offers a useful region with which to illustrate some of the more common features of hard rock hydrogeology. The oldest rocks occur in the north of Wales and are mainly metamorphic and igneous Precambrian and Cambrian rocks. Central Wales is dominated by Lower Palaeozoic sediments (Ordovician and Silurian), which occur from the south-west to the north-east of Wales. Soil cover is typically thin, particularly in parts of Snowdonia where exposed bedrock outcrops over large areas. Till and associated glacial deposits are widespread on the lower-lying ground but tend to be absent in many upland areas. Alluvium occurs in many valleys and there are large groundwater dependent peat bogs.

The basement rocks have a low primary porosity and permeability, although many have some secondary fracture permeability and porosity. Depth of weathering tends to be shallow especially on valley sides where glacial erosion has removed weathering products. Groundwater occurs in a shallow weakly permeable aquifer that is capable of maintaining rural domestic and limited agricultural and industrial demand. Characteristic features of these shallow weathered aquifers are summarised in Table 1.

Wales enjoys a maritime climate, typically receiving over 1000 mm per year, seasonally biased towards the winter months. The distribution of rainfall varies, with the highest average annual totals approaching 3000 mm in the mountainous areas of Snowdonia and the Brecon Beacons.

2.0 GROUNDWATER OCCURRENCE EXAMPLES

2.1 THE PRECAMBRIAN

The groundwater potential in the Precambrian was first documented by Greenly (1919) in his treatise on the geology of Anglesey. He identified the importance of contacts between different metamorphic rocks and between metamorphic rocks and the Silurian and Carboniferous sequences, especially low angle contacts and the contacts between dykes and country rock. Remarkably, Greenly also recognised the vulnerability of weathered fracture systems to surface pollutants.

Groundwater circulation in basement rocks is shallow and restricted to short flow paths on a local catchment scale within selected fractures. Partial superficial cover of till may contain perched water but may also inhibit rainfall recharge to bedrock. There is little storage available in the basement and discharges to surface may be intermittent and quick to react to rainfall events. The hydraulic flow patterns are complex and conventional hydraulic theory may not apply. Nevertheless, the ancient hard rocks do contain groundwater, and it is a resource which is often under-used in Britain although it has been widely developed in areas such as Scandinavia (Banks and Robins, 2002). Yields from springs, wells and boreholes are generally small; aquifer properties are not easy to evaluate.

2.1.1 A statistical approach in Anglesey

Statistical analysis of hydraulic data provides the most appropriate means of comparing the performance of different lithostratigraphic zones in a given area. In general this is not carried out in the UK because of insufficient data, but a data set that was collected for the Mona Complex on Anglesey for apparently quite unrelated reasons in the 1970s has allowed such an analysis (Robins and McKenzie, 2005). The well and spring data set comprises three pieces of information: grid reference, well or spring, and geological observations for most data points. The geological observations identify some wells in till only, wells and springs at the junction between till and bedrock and bedrock springs and wells in close proximity to a dyke or a lithostratigraphic contact.

Table 1 Groundwater occurrence in basement rocks (after Robins, 1999)

Occurrence	Description	Example
Shallow groundwater circulation	Groundwater are young, weakly mineralised and derive from local recharge area in a catchment scale	Much of upland Wales
Perched groundwater	Common where two or more hydraulically independent fracture systems occur, or where granular drift and bedrock are hydraulically separated – tends to issue as wet weather springs	Much of West Wales
Confined fracture flow	A fracture fed from a phreatic zone at a relatively high elevation in a catchment	The confining head tends to increase with depth beneath valley bottom (Figure 2)
Non-sustainable supplies	Water bearing fracture which is not in good hydraulic contact with a recharge source	Common upland feature
Preferred flow paths	Lines of weakness which may parallel major tectonic features and stress release features such as dominant fracture orientation.	Dominant fracture orientation, e.g. Dyfi (Glendining, 1981)
Drift aquifer storage	Groundwater in valley gravels contributes to overall storage in fractured bedrock wherever there is hydraulic continuity.	Afon Teifi (Robins et al., 2000) Rheidol (Hiscock & Paci, 2000)
Regolith storage	Granular weathering that offers high storage but removed under glacial ice	Not in Wales, but can be seen in Cornwall and the Channel Isles
Deep groundwater circulation	Uncommon except where deep fracture systems link recharge and discharge zones.	The saline spa waters at Llandrindod Wells (Edmunds et al., 1998)
Springs	Wherever a water bearing fracture intercepts ground surface.	Upland valley sides

Table 2 Distribution of springs and wells in the Precambrian Mona Complex, north-east Anglesey (after Robins and McKenzie, 2005)

Formation	Outcrop area (km^2)	Number of wells	Number of springs	Wells Km^{-2}	Springs km^{-2}
South Stack Group	18	77	18	4.3	1.0
New Harbour Group	133	373	92	2.8	0.7
Holyhead Quartzite Formation	3	3	0	1.2	0.0
Gwna Melange Formation	61	183	66	3.0	1.1
Church Bay Tuffs and Skerries Grits	13	45	12	3.4	0.9
Central Anglesey Shear Zone and Berw Shear Zone	28	58	33	2.0	1.2
Coedana Complex	38	88	61	2.3	1.6
Coedana Granite	29	76	37	2.6	1.3

Spring discharges from the basement rocks in north-west Anglesey and Holyhead Island are, for the most part, small, typically less than 2 l s^{-1}. Analysis of the density distribution of both springs and wells for each bedrock formation is given in Table 2. The data include those wells and springs that derive only from the superficial cover and from the contact between till and bedrock. As the till coverage is near complete, the drift wells and springs are likely to be roughly evenly distributed. The overall well and spring densities, be they in bedrock or drift, therefore, dominantly reflect changes in bedrock properties, the Quaternary properties being areally consistent.

There are 3.7 springs and wells per km^2 in north-west Anglesey. The density of wells is greatest over the South Stack Group and least over the Holyhead Quartzite Formation, whereas the springs are more evenly distributed although none were found over the Holyhead Quartzite Formation. This suggests that the New Harbour Group and South Stack Group and other formations in the Mona Complex offer more favourable conditions for shallow groundwater than the Holyhead Quartzite Formation.

There are a number of additional features that the data illustrate. Increased fracturing in the vicinity of dolerite dykes accounts for the success of well digging in much of the South Stack Group, which has 4.3 wells km^{-2}, but only 1.0 springs km^{-2}, and the New Harbour Group, which has 2.8 wells km^{-2} and 0.7 springs km^{-2}. The presence of distinct foliation in the Gwna Melange Formation and the Church Bay Tuffs and Skerries grits also enhances the success of well digging in these rocks.

2.2 THE CAMBRIAN

Groundwater occurrence and circulation in the Cambrian rocks, which are largely sedimentary in origin, is much the same as in the Precambrian. Groundwater is contained largely in the near surface weathered and fractured zone which offers little storage potential with transport confined to dilated joints and fractures. Flow paths are typically short and shallow and of catchment scale. Spring discharges occur where fracture systems intercept the surface and along valley bottoms to provide baseflow to surface waters. Steep topography over much of the Cambrian outcrop provides additional transport of 'groundwater' via soil or scree interflow; consequently Base Flow Indices may be misleading in such terrain. Although there are numerous springs associated with the Cambrian outcrop some are sourced partly from overlying superficial deposits.

2.2.1 Flowlogs at Dinorwic

Detailed engineering investigations were carried out in exploratory boreholes in the Llanberis Slate Formation during the construction of the Dinorwic Pumped Storage Scheme in the 1970s (Robertson, 1974). Heat pulse flow logs of two of the boreholes measured under non-pumping conditions are shown in Figure 1. These clearly show upward movement of groundwater from the interception of the lowest active fracture in each borehole EP4 and EP9, both situated in the valley bottom. The upward flow continues to a point near the top of the water column in both boreholes. It demonstrates the increasing head with depth on active fractures in valley bottoms, and reflects the interception of successively longer flow paths, each upwelling along the valley bottom and derived from a higher recharge elevation on the valley side (Figure 2). By contrast, exploratory boreholes EP5 and EP7 in the same vicinity were static throughout the borehole column.

Boreholes EP4 and EP7 were also flow logged during pumping at 2 l s^{-1}. The work showed that all the pumped water in EP4 derives from the uppermost 15 m of the borehole, reflecting the location of active fractures seen in the static log (Figure 1). Borehole EP7, which showed no upward transport of water in the non-pumped state, revealed a production zone between 4 and 10 m below ground level, again indicative of shallow groundwater circulation. Pumping was only maintained for brief periods at Dinorwic and sustainable yields are likely to be considerably less than the recorded 2 l s^{-1}.

Figure 1 Flow meter logs at Dinorwic

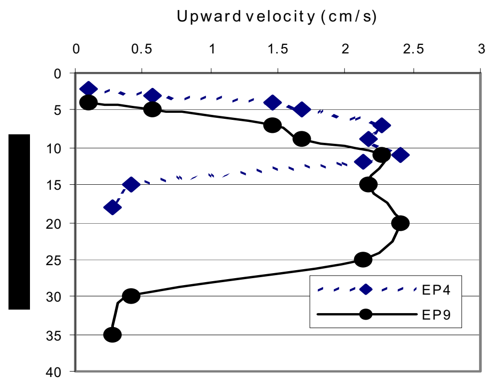
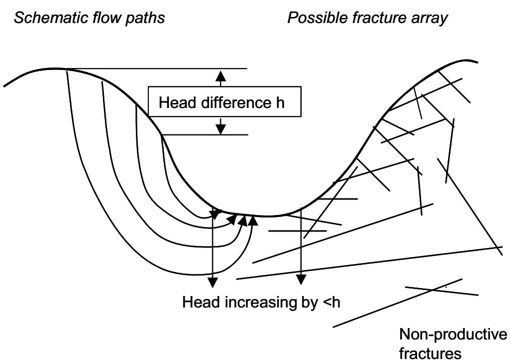


Figure 2 Schematic valley cross section



2.3 THE ORDOVICIAN AND SILURIAN

The diverse lithologies that are present in the Ordovician and Silurian in Wales exhibit a range of hydraulic properties. This diversity contrasts with southern Scotland and south-east Northern Ireland where the dominant lithologies are greywacke sandstone, siltstone and mudstone, and the strata are described as weakly permeable and capable only of supporting isolated springs and shallow wells (Robins, 1999). In Wales, some of the Ordovician and Silurian strata are also weakly permeable and do not form a useable aquifer, but there are other areas in which the strata are relatively productive.

The degree of glaciation was also significantly less in Wales (except for Snowdonia) than it was in north Britain. Consequently, the removal of the weathered zone by the ice sheets was less effective and the weathered and fractured uppermost layer of rock is partly preserved in Wales. In some areas the effects of glacial frost shattering enhances the near surface permeability of the rock. Tectonic activity has induced discontinuities throughout much of the Welsh sequence and bedding plane fractures, and sub-vertical breaks are commonplace. The boundaries between lithologies and between volcanic facies tend also to be marked by dilated joints sufficient to allow groundwater transport. Flow boundaries may be controlled by fracture orientation which dictates the preferred groundwater flow direction. Significant groundwater storage, however, tends to be restricted to the coarser arenaceous deposits. In general, the water table tends to be shallow in most areas.

2.3.1 Analysis of the upland Afon Dulas sub-catchment

One of the earliest investigations into groundwater occurrence in the Ordovician and Silurian was a reconnaissance study of the Afon Dulas sub-catchment of the Dyfi north of Machynlleth (Glendining, 1981). The catchment comprises a series of folded, well-cleaved and fractured turbiditic mudstones and slates with a north-easterly strike. The superficial cover includes head and scree deposits, peat and valley alluvium. The cleavage planes trend north-easterly and are sub-vertical to 60^{o} in dip, the main joints are normally vertical and are orientated between 120^{o} and 140^{o}, the faults also are sub-vertical. Surface drainage is strongly influenced by this structure, with the Tal-y-Llyn and Dyfi valleys following major fault lines and many first order streams following the 120^{o} joint directions.

The bulk catchment properties suggest that total river flow equates to total effective rainfall. This assumes that changes in storage and soil moisture deficit are negligible over the long term and that underflow from the catchment is small. Baseflow separation of the catchment runoff was calculated, and divided between alluvium (15 km^2 in area in the catchment) and bedrock (456 km^2). Infiltration into the alluvium was assumed to be equal to total effective rainfall. The effective rainfall over bedrock was divided between the amount needed to make up the overall baseflow from the catchment plus the runoff (Table 3), i.e. bedrock baseflow was calculated from the total baseflow, derived from baseflow separation estimate, minus the alluvium baseflow. Again it assumed that baseflow equals infiltration in the long term. This shows (Table 3) that the average annual infiltration to the bedrock is 316 mm or 19% of the effective rainfall (against 1685 mm or 100% to the alluvium). This is likely to be an overestimate as it disregards soil and scree interflow, short flowpath discharge through the near valley bottom weathered zone and the capacity of the rock to accept recharge.

The Glendining (1981) study assigns percentage flow to shallow, intermediate and deep flow paths and uses estimates of hydraulic gradients for each flow path to enable the overall hydraulic conductivity for the rock mass to be calculated. The value is of the order 10^{-3} m d^{-1}, however, the near surface weathered zone may be of the order 1 m d^{-1}.

Table 3 Effective infiltration (equal to baseflow) divided between alluvium and bedrock in the Afon Dulas catchment (after Glendining, 1981)

Year	Total flow (mm)	Baseflow (mm)	Effective rainfall (mm)	Alluvium (15 km^2) infiltration m^3 x 10^6	Bedrock infiltration (456 km^2) infiltration m^3 x 10^6	Bedrock infiltration (mm)
1962-1963	1195	312	1393	21.0	126	276
1963-1964	1017	275	1201	18.0	111	244
1964-1965	1713	333	1842	27.6	129	283
1965-1966	1679	314	1909	28.6	119	261
1966-1967	-	-	1715	25.7	-	-
1967-1968	1656	444	2131	32.0	177	388
1968-1969	1224	399	1453	21.8	166	364
1969-1970	1410	417	1774	26.6	170	372
1970-1971	1355	382	1750	26.2	154	337
Mean	1406	396	1685			316

2.3.2 Groundwater on a catchment scale

Robins et al., (2000) investigated the occurrence of groundwater in the Silurian and Ordovician rocks of the Teifi valley, and Hiscock and Paci (2000) concentrated on the more arenaceous deposits of the Rheidol catchment. Both these investigations highlight the interaction between groundwater in bedrock and in the superficial cover particularly along valley bottoms.

The bedrock in Afon Teifi comprises shales and slates of Ordovician and Silurian age. Springs are common and issue primarily from discontinuities in the shale, or the contact between bedrock and the overlying superficial material. Many of the springs are seasonal reflecting low storage capacities. Storage may be enhanced where fractures are in hydraulic contact with overlying superficial deposits which possess intergranular storage, these occur in some valley bottom areas.

Sustainable yields from bedrock are low, although adequate for many private uses. Typical sustainable borehole yields are around 0.3 l s^{-1}. Spring flows occur up to 2 to 3 l s^{-1}, and exceptionally 5 l s^{-1}, but flows of less than 1 l s^{-1} are more typical. Boreholes are generally about 40 m deep; exceptions include one borehole which is 140 m deep. Short duration pumping tests indicated transmissivity of the order 5 x 10^{-1} m^2 d^{-1}, but complicated by the presence of boundary conditions and dewatering of shallow fractures during tests.

The water level is rarely more than 10 m from the surface, irrespective of the ground elevation. No clear piezometric surface can be created from water level data for boreholes and spring elevations. This reflects the nature of a fractured aquifer beneath relatively steep surface topography, where perching is common. A best estimate of the quantity of groundwater abstracted from the catchment (based on data collected by the Environmental Health Departments (Table 4) suggests that less than 2 Ml d^{-1} groundwater is being used in the catchment area.

Table 4 Groundwater consumption in the Teifi catchment (principally from bedrock) excluding the Alwen public supply source which draws from superficial gravels

	Estimated daily consumption (m^3)	Estimated number of sources	Total abstraction (m^3 d^{-1})
Domestic - single property	0.6	809	485.4
Domestic - <25 people	1.2	83	99.6
Farm (livestock)	1.5	68	102
Farm (dairy)	6.5	132	858
Commercial (hotel, youth hostel, abattoir, quarry, etc.)	8.0?	20	160
Total		1112	1705 (622 Ml a^{-1})

Runoff and potential evaporation exceed precipitation, but runoff (river flow) includes groundwater baseflow (infiltration). As the Base Flow Index is 0.54 and the long term average annual runoff near the base of the catchment is 999 mm (CEH/BGS, 2000), about 540 mm derives from groundwater discharge, the majority of this from valley bottom alluvial deposits. This represents a renewable resource of 540 Ml a^{-1} per square kilometre of aquifer, a large value by comparison to the estimated 622 Ml a^{-1} withdrawn from all the boreholes, wells and spring discharges throughout the whole catchment.

Using a transmissivity value of 0.6 m^2 d^{-1} (from pumping test analysis), an average catchment width of 17 km, and estimating the hydraulic gradient to be equal to the gradient of the river (2.5 x 10^{-3}), then Darcy's Law indicates that the overall throughflow along the length of the valley is 25 m^3 d^{-1} or only 9 Ml a^{-1}. This is a small amount compared to the total estimated baseflow (540 Ml per square kilometre of aquifer) and it shows that the majority of the baseflow component of river flow derives from local recharge and discharge via flow paths perpendicular to the valley sides, and not from longitudinal flow paths down the length of the valley. Abstraction and spring flow are small elements of the overall infiltration indicated by baseflow indices.

Hiscock and Paci (2000) studied the contrasting Rheidol catchment, which enters the sea at Aberystwyth. The principal difference is that a more granular and generally more water bearing bedrock is present in the Rheidol than in the Teifi. Other differences include surface waters polluted by mine water discharge from former metal mining activities, and stream regulation for hydropower. The bedrock comprises Silurian grits and shales, of which the uppermost formations offer the better conditions for groundwater occurrence in fractures and minor groundwater abstractions. This reflects a decrease in metamorphic grade and increase in depth of weathering in the younger Silurian formations coupled with occurrence of sandstones in the upper part of the sequence.

The overall porosity is between 2 and 4%. The depth of weathering is up to 20 m, and brick lined pits have been effectively used to capture springs and divert shallow groundwater flow to gravity fed systems for domestic usage, although the majority of sources relate to contact with superficial deposits. In the upper parts of the catchment there are distinct spring lines parallel to the river.

The Rheidol catchment covers an area of 182 km^2. Hiscock and Paci note there are 65 sources providing 3.6 Ml d^{-1}. Twenty nine of the sources are in bedrock and ten are in superficial deposits in contact with bedrock. The estimated water balance for the catchment using an evapotranspiration value based on baseflow separation and a Base Flow Index of 0.51 is shown in Table 5.

Table 5 Comparative water balance estimates (mm a^{-1}) for the Teifi and Rheidol catchments (after Robins et al., 2000; Hiscock and Paci, 2000)

	Teifi	Rheidol
Rainfall	1349	1790
AE	544 (Morecs) 350 (baseflow separation)	753 (baseflow separation)
Runoff	459	667
Baseflow	540	363
Groundwater abstraction	Small	7

2.3.3 Deep circulation to the Central Wales Spas

There is evidence of some deep groundwater circulation in Central Wales. The saline waters of the spa sources in the Llandrindod and Builth Wells area of Central Wales have been a focus of interest since Roman times. The Builth Inlier is characterised by weakly permeable metasedimentary and volcanic rocks with a deeper than normal fracture system associated with the north-westerly trending Tywi Lineament. Small volume discharges of iron rich and sulphur rich waters, some with total dissolved solids greater than 16 000 mg l^{-1}, suggest that some deeper than normal groundwater flow paths exist within the Ordovician and Silurian strata (Edmunds et al., 1998).

The discharge from all the springs including sources at nearby Llangamarch and Llanwrytyd are collectively < 1 l s^{-1}. The high salinities indicate a slow passage to considerable depth, there being no evaporite or hydrothermal deposits in the area. The discharge temperature is close to mean annual air temperature between 11 and 13 ^{o}C, reflecting a slow upward journey of small flow volumes which equilibrate with the surrounding rock temperatures near surface before discharging. Stable isotope and radiocarbon evidence suggest the waters are of Late Pleistocene age.

2.3.4 Hydrochemical indicators in the Wye Valley

Investigation of local scale transport process in the Upper Severn catchment at Plynlimon provides further insight into the hydraulics of upland hard rock catchments. This work specifically tackles the issue concerning the role of groundwater in sustaining baseflow and its important contribution to storm flow as demonstrated by isotopic indicators analysed for groundwater and surface water during dry and during rainfall events. Fractal analysis of the chloride output demonstrated that there was a range in travel times to groundwater arriving in the stream (Kirchner et al., 2001), and isotopic evidence shows that the stream waters lie on a mixing line between groundwaters and rainfall.

Haria and Shand (2004) have carried out intensive investigations in a sub-catchment of the upper Severn near Plynlimon. The transect is some 50 by 10 m in area and is perpendicular to the stream and includes boreholes into weathered bedrock as well as soil piezometers. The time series physical and chemical data highlight the role of groundwater in stream flow generation. Key conclusions are that the upper 1.5 m saturated weathered zone contributes significantly to baseflow with the less weathered zone to 10 m depth also active. It is a complex system with discrete flow paths in individual (confined) fractures which mix at the valley bottom. Although discharge responds rapidly to rainfall some older upwelling water is included in the baseflow.

3.0 CONCLUSIONS

Groundwater occurrence in shallow fractured aquifers of Wales is characterised by catchment scale aquifer units, short and shallow flow paths dictated by fracture availability and direction, and complex inter-relationships with superficial strata and surface waters. Recharge to these aquifer units is not easy to determine. The groundwater resource potential is modest, but groundwater provides a useful social asset to many rural communities in Wales, and baseflow sustains upland stream low flows.

4.0 ACKNOWLEDGEMENT

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THE KNOCKATALLON AQUIFER IN COUNTY MONAGHAN: A BEDROCK AQUIFER IN IRELAND UNDER SIGNIFICANT STRESS FROM PUMPING

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ABSTRACT

The Knockatallon aquifer is a fractured bedrock aquifer in north County Monaghan covered by thick (up to 53m) low permeability subsoils. Since the 1980's the aquifer has been under significant stress from abstraction, so that by 2000 groundwater levels had become depressed by up to 40m below pre-pumping levels. Since then, however, groundwater levels appear to have stabilised, indicating that abstraction rates may be in balance with aquifer recharge. This paper summarises an investigation into quantifying recharge to the Knockatallon aquifer that forms part of an EPA-funded study that focuses on developing a quantified link between recharge and groundwater vulnerability.

1.0 INTRODUCTION

The Knockatallon aquifer is a fractured bedrock aquifer near Tydavnet in north County Monaghan (Figure 1). Abstraction since 1983 by the Tydavnet Group Water Scheme (TGWS) has caused groundwater levels in the aquifer to fall substantially. For the year 2000 an average of 1,000 m^3/day was being abstracted. Groundwater levels are locally depressed by up to 40 m below pre-pumping water levels. Kelly (2001) attributed the falling water levels to low recharge as the aquifer is covered by substantial thicknesses (up to 53m) of low permeability subsoils.

In 2003 TCD began a monitoring programme on the Knockatallon aquifer as part of an EPA-funded study aimed at developing a quantified link between recharge and groundwater vulnerability. The study was initiated because, under the Water Framework Directive, aquifers are required to have good status in terms of groundwater quantity and quality, and a knowledge of aquifer recharge is necessary to establish quantitative status. The Tydavnet area was selected as an example of a regionally important bedrock aquifer in a low vulnerability area. (Note that, in the light of results from this study, the aquifer classification has been modified to locally important.) Other areas being investigated represent other combinations of aquifer type and vulnerability category.

Methods for the estimation of recharge can be grouped into the following approaches (Misstear and Wijnen, 2004):

- Inflow estimation by soil moisture budgets, infiltration coefficients, soil moisture flux approaches, lysimeters and tracers;
- Aquifer response analysis using groundwater hydrographs;
- Outflow estimation, based on river baseflow determinations;
- Catchment water balance and modelling.

In the Tydavnet area, the recharge estimates are based upon inflow estimation (including recharge coefficients, Darcy flux calculations and tracers), hydrograph analysis and river baseflow analysis. It is also proposed to test the conceptual model of the system with a groundwater flow model.

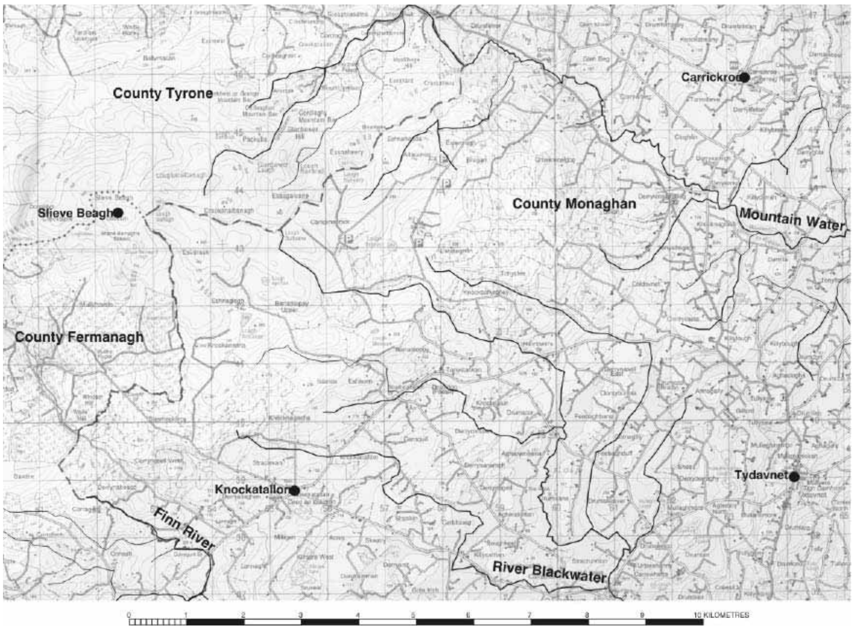


Figure 1 The location of the Tydavnet area in north County Monaghan

2.0 THE TYDAVNET AREA

2.1. TOPOGRAPHY

The Tydavnet area lies in northwest County Monaghan, and is bounded to the west and north by counties Fermanagh and Tyrone, respectively (Figure 1). Ground elevation generally decreases from the northwest to the southeast, the highest area being Slieve Beagh at 380m and the lower area being a plain covered by drumlins, which falls to about 40m along the Blackwater River in the southeast. Most of the mountainous area is covered by heather, but is afforested by fir along parts of its middle slopes; the lower area is agricultural land dominated by pasture.

2.2. SURFACE WATER

All surface water drainage within the study area is part of the Blackwater catchment, except for a relatively small area (6km^2) in the west that drains to the Finn River, a tributary of the Erne. The Blackwater River has a flow gauge station at Cappog Bridge (approximately 4km south of Tydavnet), which measures drainage from the upper 65km^2 of the Blackwater Catchment. The flow gauge station at Glaslough (about 8km east-northeast of Tydavnet) measures the flow for an area of 72km^2 comprising almost the entire catchment of the Mountain Water River, which is the main tributary of the Blackwater River in the area. These flow gauges have autographic recorders that are maintained by the Office of Public Works.

2.3. SOIL AND SUBSOIL GEOLOGY

On the upper slopes around Slieve Beagh soil cover is mostly blanket bog but some patches of sandstone and shale bedrock are exposed. Subsoils are largely absent but become increasingly thick on the middle slopes, where the tills are largely derived from sandstones and shales. The lower flanks of the uplands as well as the lowland plains are dominated by drumlins (up to 40m in height) that generally have a northeast-southwest orientation. The area generally is poorly drained, as indicated by the abundance of rushes and field drains. Here, the subsoils typically exceed 40m and can be divided into two main units: (i) an upper till, derived from sandstone and shale parent material, which has occasional sand and gravel bodies that range in size from lenses several metres across to an esker deposit several kilometres in length, and (ii) a lower till derived from limestone parent material, which has no observed sand or gravel bodies. The upper till appears to be a continuation of the sandstone and shale-derived subsoils that are observed on the middle slopes.

2.4. BEDROCK GEOLOGY

The Carboniferous stratigraphy of counties Monaghan, Fermanagh and Tyrone is geographically divided into several contemporary successions (Geraghty *et al*., 1997). In the Tydavnet area of north Monaghan the Erne Succession comprises the Benbulben Shale Formation, the Dartry Limestone Formation and the Meenymore Formation, which includes the Carnmore Sandstone Member (Figure 2); the Maydown Limestone Formation of the Armagh Succession is present in the east of the area. The structural geology of the region includes a series of northeast-southwest trending anticlines and synclines formed during the Variscan Orogeny (late Carboniferous). Major faults trend roughly northwest-southeast. Faulting in the Knockatallon area is likely to be present but unmapped due to the thick subsoils. The bedrock units in the Knockatallon-Tydavnet area dip gently (by 2-4°) to the northwest (Figure 3).

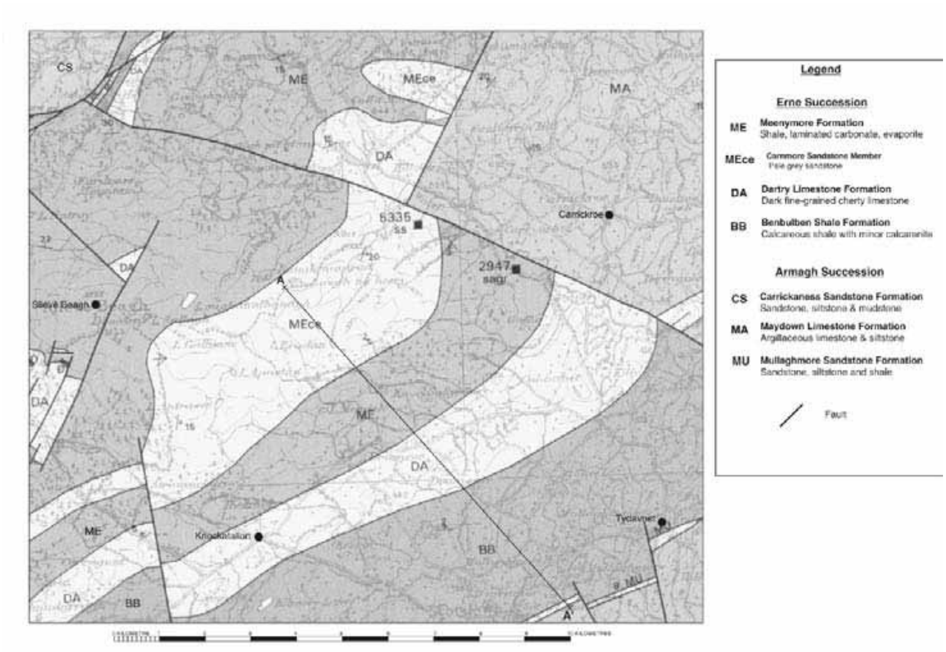


Figure 2 The geology of the Tydavnet area (Geraghty *et al*, 1997).

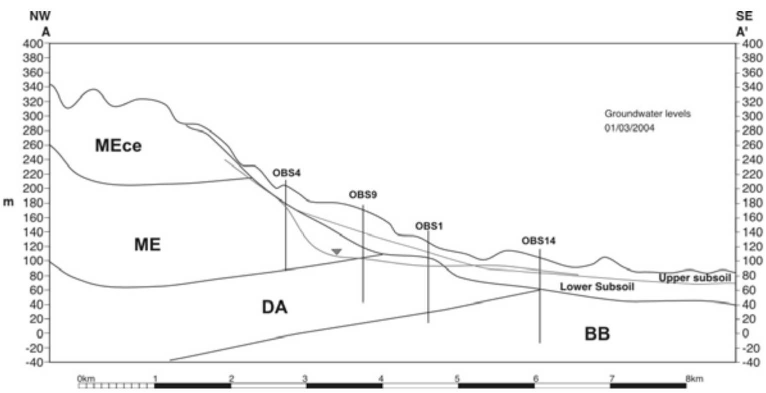


Figure 3 Cross section A-A' showing subsoil geology, bedrock geology and potentiometric surface in March 2004 (for location of section and key to bedrock geology see Figure 2)

2.5. HISTORY OF GROUNDWATER ABSTRACTION

At present, a total of five supply wells are active (wells PW-A, B, C, D and E in Figure 4). In addition to these supply wells, a total of 14 monitoring wells, which include abandoned trial wells (originally commissioned by Monaghan County Council), are used to monitor groundwater levels.

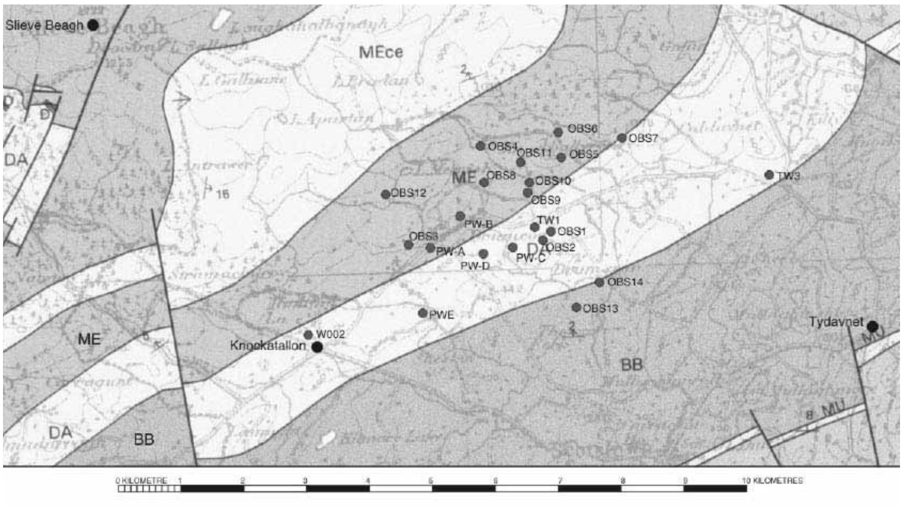
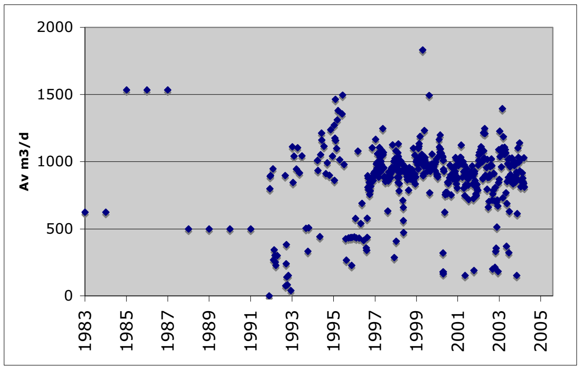


Figure 4 Location of pumping wells (PW) and monitoring wells (OBS) in the Knockatallon aquifer (see Figure 2 for key to bedrock geology)

Since the initiation of the group scheme in the 1980s, groundwater levels have been substantially lowered and the aquifer has changed from being confined to unconfined in the vicinity of the wellfield (Figure 3). In response to falling water levels, the TGWS installed additional supply wells to reduce the abstraction rates on individual wells whilst maintaining supply to meet demand. PW-A and PW-B are the main abstraction wells within the group scheme; the other wells are used to supplement the supply. Cumulatively, the TGWS abstracts an average of 1000 m^3/day (Table 1).

Table 1 Summary of groundwater abstractions (data provided by the TGWS).

Well Reference	Initial pumping rate m^3/day		Later pumping rates (examples) m^3/day		Average Total Daily Pumping Rates (m^3/d)
PW-A	1983	623 (av)	1988	500 (av)	
PW-B	1993	1000-1500	1995	250-600	
PW-C	1996	450-600	1998	300-400	
PW-D	1997	350-750	1998	300-400	
PW-E	2000	160-330	No Change		
MCC	1985	912	Well abandoned 1988		
TGWS-Burns	1992	300-600	Well abandoned 1993		

3.0 HYDROGEOLOGY

3.1 THE KNOCKATALLON AQUIFER

Kelly (2001) identifies the Knockatallon aquifer as consisting of the Dartry Limestone Formation and the Meenymore Formation; this was delineated as a regionally important fissured aquifer (*Rf*) during the compilation of the Monaghan Groundwater Protection Scheme (GSI, 1999). This assessment was based on the relatively high productivity indicated by testing of the TGWS supply wells when they were commissioned. Table 2 summarises the original pumping test data, and the interpreted values of transmissivity and storage coefficient (Kelly, 2001). The aquifer has a modest overall transmissivity, but with local zones of high hydraulic conductivity, and a low storativity.

Table 2 Summary of pumping test data for the Knockatallon aquifer (Kelly, 2001).

Well Reference	PW-A (1981)*	PW-B (1992)	PW-C (1996)
Test duration	13.5 hrs	14 days	5 days
Aquifer state at start	Confined	Confined	Confined
Aquifer state at end	Confined	Unconfined	Unconfined
Pumping rate m^3/day	1,178→1,364	7,200→6,546	1,300
Well depth m	50.30	123.75	123.00
Till Thickness m	30.50	38.00	34.00
Total screen/open hole m	19.80	36.50	18.00
Transmissivity (T)	76 m^2/day	72-88 m^2/day	40-47 m^2/day
Storativity (S)	2×10^{-3}	4×10^{-2}	2×10^{-3}
Final drawdown m	15.09	14.14	10.73
Steady state	No	No	No

*Note: The well numbering in the area is rather complex, and PW-A in this table refers to the original trial well which was tested in 1981; the current PW-A was drilled in 1994 and is 126m deep.

The well locations with respect to the geological formation boundaries on the geological map for Monaghan (GSI, 1997) suggest that the active pumping wells tap the Dartry Limestone Formation, and that some wells or observation boreholes have open sections in the overlying Meenymore Formation. However, the original drilling logs are not sufficiently detailed to be able to differentiate formation boundaries in the borehole sections. Therefore, geophysical logging was carried out in six of the boreholes to attempt to identify the contributing aquifer, and to investigate the inflow characteristics. The logs run were natural gamma and CCTV (in the cased and uncased sections of the boreholes) and caliper, flow and temperature/conductivity logs (in the open hole intervals only).

The natural gamma logs were used to try to identify the contact between the Meenymore Formation (predominantly shales) and the Dartry Limestone Formation in each borehole. The logs suggest that the wellfield abstracts from the Dartry Limestone Formation. CCTV and caliper data were used to identify fracture frequency and showed the upper 8-12m of the bedrock (of both formations) to be particularly well fractured and weathered. Fracture apertures decrease with depth below this zone. Conductivity and temperature data were used to map flow systems within each well. In OBS4, which is the only well entirely located within the Meenymore Formation, the temperature/conductivity logs suggest that water flows into the well via fractures within the weathered zone near rock head, and flows out of the well via a fracture zone at about 70m below this depth. The zone of inflow is associated with extensive bacterial growth. No inflows were detected into any of the wells from behind the upper casings.

3.2 GROUNDWATER LEVELS AND PIEZOMETRY

The natural (pre-abstraction) flow direction in the aquifer is assumed to have been generally from northwest to southeast, reflecting the local topographic gradient (Figure 1). Most of the groundwater in the aquifer would have flowed in the direction of the Blackwater and its major tributary the Mountain Water, except for a small volume that probably drained to the Finn River in the west. The long-term abstraction has altered the flow pattern by directing flow towards the pumping wells and developing a cone of depression around the wellfield (Figure 5). The monitoring wells show that drawdown has occurred both within the Dartry Limestone Formation and the Meenymore Formation but that whereas gentle hydraulic gradients occur in the cone of depression within the Dartry, steeper hydraulic gradients occur within the Meenymore, consistent with the Meenymore having a lower transmissivity than the Dartry (Figure 3).

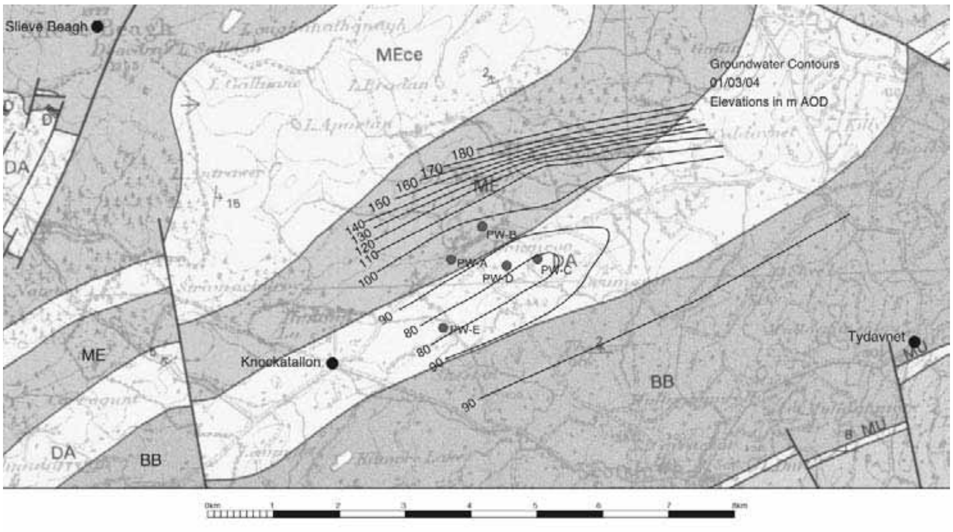


Figure 5 Piezometric levels (mAOD) in the Knockatallon aquifer (01/03/2004).

An example of a hydrograph from a monitoring well (OBS 2) within the wellfield zone of contribution (ZOC) is given in Figure 6. This shows a substantial lowering of groundwater levels since October 1997, when the observation well was commissioned. A reduction in pumping rates in PW-C and PW-D led to a temporary recovery in groundwater levels between February and June 1998, but groundwater levels continued to fall from July 1998 for a further year. In mid-1999 groundwater levels ceased their steep downward trend and have remained relatively stable since then. This stabilisation of groundwater levels is also observed in other wells within the monitoring network, suggesting that the present abstraction rate (1000m^3/day) by the TGWS is in equilibrium with recharge to the aquifer.

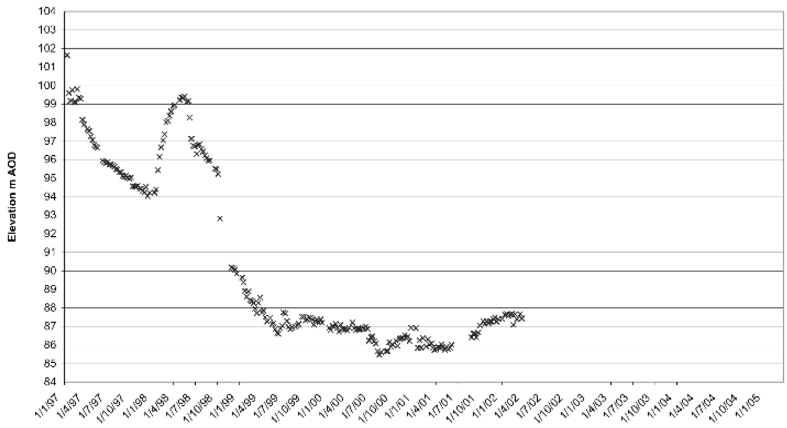


Figure 6 Hydrograph for OBS2.

An interesting feature of some of the monitoring wells is that they show significant air inflows and outflows. There are a number of possible explanations for this behaviour: earth tides, barometric effects or the effects of air being sucked in or forced out of the unsaturated zone below the low permeability subsoil cap in response to abstraction. Although pumping occurs on a regular schedule there is no obvious cyclical pattern apparent from the observations made to date. Monitoring of groundwater levels, atmospheric pressure and pumping rates will continue as part of this project so that any long-term correlation with airflows into and from the boreholes can be made.

3.3 GROUNDWATER CHEMISTRY

The groundwater chemistry has been studied by Kelly (2001). From the point of view of recharge, it is the evidence relating to groundwater residence time that is of most interest. In this regard, there is some evidence of ion exchange having occurred in the aquifer, with lower calcium and higher sodium concentrations found in the wellfield than in the boreholes up-hydraulic gradient. Another indicator of residence time is the presence of fluoride in some of the boreholes in the wellfield, especially PW-B (1.87mg/l fluoride on 21/01/2001). (The TGWS blends water from PW-B with water from PW-A, which has a fluoride concentration less than the MAC of 1mg/l). Fluoride typically occurs in groundwater by the dissolution of fluorite, apatite and micas. In the Knockatallon aquifer the high fluoride may originate from evaporite deposits present within the Meenymore Formation. There are a number of solubility controls for fluoride in groundwater, one of which is the mineral fluorite, with higher concentrations of fluoride often being associated with low calcium concentrations. In this area the fluoride concentration does appear to be negatively correlated with calcium. Also, there appears to be a positive correlation between fluoride and magnesium, and especially, sodium concentrations, suggesting perhaps that its concentration is influenced by ion exchange processes.

4.0 RECHARGE ESTIMATION

Work on recharge estimation is on-going, therefore only preliminary figures are presented here. Owing to the presence of thick (typically greater than 40m) low permeability subsoils covering the Knockatallon aquifer, direct recharge in the vicinity of the wellfield is expected to be low. A simple calculation will serve to illustrate this point. Assuming:

- the area of subsoil within the ZOC to the wellfield is approximately $14km^2$ (Figure 5);
- the effective rainfall calculated for Clones using the Penman-Grindley method is 512mm (albeit that the effective rainfall in the Tydavnet area may be somewhat higher); and
- that the current average withdrawal from the aquifer of around $1000m^3/d$ is approximately in balance with recharge, as suggested by the hydrograph in Figure 6;

then the average annual recharge through the subsoil would be 26mm, or 5 percent of the effective rainfall. This represents an upper limit for the recharge through the subsoil. When the low permeability and large thickness of the subsoil in the wellfield area are taken into account, together with indications of some modern recharge (see below), then the recharge coefficient is likely to be less than 5 percent. Such a low value of recharge coefficient is consistent with findings elsewhere in Ireland for areas with thick low permeability tills (Fitzsimons and Misstear, 2005).

A simple calculation can be made to estimate the travel time for any recharge water entering the bedrock aquifer via the overlying subsoil. Assuming:

- an average hydraulic conductivity for the lower, more clayey subsoil of $1 \times 10^{-9}m/s$;
- that this low permeability subsoil is about 20m thick, and
- has a porosity of 40 percent;

then a Darcy flux calculation (with saturated flow conditions) indicates a travel time through this layer of about 250 years. If the subsoil is the major pathway for recharge, the groundwater therefore would be expected to be 'old', as is indeed suggested by some of the hydrochemistry data (Section 3.3). It was decided to investigate the age of the groundwater further by sampling for chlorofluorocarbons (CFCs). CFCs are anthropogenic compounds that have been occurring in increasing amounts in the atmosphere since 1940. If CFCs are present in groundwater then their concentration can be used to indicate which year since 1940 that recharge occurred. However, this assumes uniform direct recharge to the aquifer. If direct and indirect recharge pathways are present then the CFC analysis provides an average age for mixed recharge. Samples taken from PW-A and PW-C both indicated the age of the groundwater as 1979. As shown by the calculation above, this relatively young recharge age cannot be achieved by direct recharge through the subsoil; as such the CFC analysis suggests that the main recharge is not via the subsoil, but from another source.

Subsoil mapping by the Geological Survey of Ireland shows that, north of OBS4 (Figure 4), the subsoils thin rapidly and that the Carnmore Sandstone Member of the Meenymore outcrops on the higher ground. It is therefore considered likely that the main mechanism for recharge to the

Knockatallon aquifer is via the Carnmore Sandstone Member, with the water moving downgradient in fractures mainly located along the extensively weathered rock head of the Meenymore and Dartry formations.

Discharge areas from the Knockatallon aquifer will be associated with the topographic lows of the Blackwater and Mountain Water. Flow data are available from both rivers, although at locations well downstream of the study area (Section 2.2). The hydrographs of both rivers are quite 'flashy', consistent with a relatively small groundwater component. Preliminary analyses show a Baseflow Index (BFI) for both rivers of around 23%, somewhat higher than would be expected for this area, although the estimates are very sensitive to the baseflow separation method used and require further investigation.

5.0 CONCLUSIONS

The interim conclusions of this investigation are:

1. The Knockatallon aquifer has indeed been under stress from pumping, although there are indications that an approximate equilibrium may now have been reached between recharge and abstractions. Long-term water level monitoring is required to confirm this.
2. The recharge coefficient for the low vulnerability areas is low, probably less than 5 percent.
3. The main source of groundwater inflow to the Knockatallon aquifer is likely to be from recharge to the Carnmore Sandstone Member of the Meenymore Formation, which outcrops on high ground northwest of the wellfield.

Based upon the findings of this project to date, the GSI has modified the status of the Knockatallon aquifer to locally important. Future work in the Tydavnet investigation will include the preparation of a groundwater flow model to test the conceptual model presented here.

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CHANGING PRECIPITATION SCENARIOS: PRELIMINARY IMPLICATIONS FOR GROUNDWATER FLOW SYSTEMS AND PLANNING

Conor Murphy, Rowan Fealy, Ro Charlton and John Sweeney (NUI Maynooth)

ABSTRACT

Statistical downscaling of a suite of three global climate models for two emission scenarios are used to produce precipitation scenarios for Ireland to 2090. One of these was used to drive a rainfall-runoff model for the River Boyne. The model was calibrated over the 1961-90 base period, validated using 1991-2000 data and run for three future time periods using downscaled GCM output. Significant changes in monthly flow regimes, soil moisture storage and groundwater storage were noted, with summer flows typically reduced by 20%. Negative changes in soil moisture storage also resulted, with soil moisture deficits increasingly extending into the Autumn as the century proceeds. Such a situation is seen to potentially compromise groundwater recharge in individual years and an increasing lag in groundwater recharge was detected. By the 2080s the groundwater recharge lag has developed to the extent that spring and early summer surface flows appear to be still benefiting from winter groundwater recharge while by late autumn groundwater is seriously depleted due to drier summer conditions. Serious implications for water yield from groundwater-fed sources would thus arise in the event of a dry winter being experienced. Greater conservatism in estimating water yields from groundwater sources would seem appropriate and may require to be formally incorporated into planning procedures.

1.0 INTRODUCTION

Although much of the concerns globally relating to future climate change focus on warming aspects, it is probable that the major impacts, as far as Ireland is concerned, will relate to precipitation changes. These are likely to have far-reaching implications in a range of sectors for which forward planning is required and a pressing strategic research objective exists in seeking to quantify the probable spatial and temporal precipitation changes likely to be experienced in coming decades. Indeed significant changes appear to be already underway; with marked winter increases observed in north western parts during the past century and marked summer decreases occurring in the south-east (Sweeney *et al*, 2002). Significant change points in Irish precipitation climatology have also been identified in the mid 1970s (Mills, 2001; Kiely, 1999) though these may at least partly relate to circulation frequency changes associated with the North Atlantic Oscillation. In any event it is clear that precipitation changes may have large and diverse consequences for water management and supply and this paper seeks to examine the consequences of these particularly for groundwater systems.

2.0 THE PRODUCTION OF PRECIPITATION SCENARIOS

The relatively coarse resolution (typically grid sizes >2.5^{o}) of Global Climate Model (GCM) output limits their utility for assessing the impacts of climate change, many of which require analysis at sub grid scale. Obtaining regional scenarios involves translating the GCM output to finer spatial scales, a technique known as downscaling. One of the most widespread approaches has been the incorporation of mesoscale predictor variables in an empirical statistical technique that establishes linkages between the GCM output and surface observations. This statistical downscaling technique is based on the assumption that GCMs simulate mesoscale aspects of climate better than surface variables such as temperature and pressure. The method involves firstly establishing relationships between conservatively changing upper air variables, such as geopotential temperatures and heights and local surface observations. Over a training period, the relationship between these sets of variables is established and assumed to be robust in a changing climate situation. Since the same mesoscale variables also are outputs of the GCM, the local surface variables in a changed climate situation may then be estimated via a transfer function. Downscaling is done for individual point locations both for the baseline and future runs of the model and the differences are applied to the observational data to provide a climate change scenario.

Previous downscaling work has indicated that substantial precipitation changes may occur in Ireland by mid century (Sweeney and Fealy, 2003). Overall increases in precipitation were projected for the winter months with up to 20% more rain in the northwest. In contrast, marked decreases during the summer months across eastern and central Ireland amounting to between 25-40% of present values were projected. It must be stressed that precipitation scenarios are inherently less reliable than temperature given the spatial variability of precipitation itself and the many uncertainties of GCMs in this area and in this case were based on output from a single Global Climate Model (Hadley CM3). To address this a suite of three GCMs has been employed in current work: the Canadian Climate model (CGCM2), the Australian Climate model (CSIRO) and the UK Met Office model (HADCM3) in combination with two emission scenarios A2 and B2. The former is a high emission scenario while the latter is indicative of a less carbon intensive world. Differences are apparent between the models in terms of seasonal precipitation projections for Irish stations. The current work examines 10 different catchments (Table 1) though for this paper, given the preliminary nature of results, only the HadCM3 A2 output was employed and results are presented only for the Boyne catchment.

Table 1: Catchments studied and their location

Catchment	Area (Km^2)	Gauge	Data (days)	Mean Rainfall (mm)	Mean ET (mm)	Mean Discharge (cumecs)	Land use	Soil Texture
Suir	*3556.00*	*Clonmel*	*14610*	*2.7*	*1.27*	*48.2*	*Pasture*	*Loam*
Blackwater	*3245.70*	*Ballyduff*	*14610*	*3.1*	*1.5*	*62.3*	*Pasture*	*Loam*
Boyne	*2670.50*	*Slane*	*14610*	*2.4*	*1.22*	*35.4*	*Pasture*	*Loam*
Moy	*1980.87*	*Rahans*	*9862*	*3.9*	*1.22*	*57.9*	*Peat Bogs*	*Loam*
Barrow	*2956.00*	*Levitstown*	*11688*	*2.5*	*1.27*	*20.9*	*Pasture*	*Sandy Loam*
Brosna	*1082.50*	*Ferbane*	*14610*	*2.4*	*1.22*	*17.1*	*Pasture*	*Loam*
Inny	*1072.50*	*Ballymahon*	*10227*	*2.6*	*1.22*	*18.7*	*Pasture*	*Loam*
Suck	*1050.00*	*Bellagill*	*9498*	*2.8*	*1.22*	*25.2*	*Pasture*	*Loam*
Bonet	*371.57*	*Dromahair*	*14516*	*3.3*	*1.2*	*11.2*	*Natural*	*Clay Loam*
Ryewater	*213.90*	*Leixlip*	*14610*	*2.2*	*1.5*	*2.3*	*Pasture*	*Clay Loam*

3.0 THE RAINFALL-RUNOFF MODEL

The rainfall-runoff model employed is HYSIM (Manley, 1993). This is a conceptual rainfall-runoff model, which uses rainfall and potential evaporation data to simulate river flow using parameters for hydrology and hydraulics that define the river basin and channels in a realistic way. Although spatially lumped and hydrologically conceptual in nature, the model contains a number of parameters that can be measured from physical reality. The model is built around two sub-routines; the first of these simulates catchment hydrology while the second simulates channel hydraulics. The complete flow diagram of the structure of the model is given in Figure 1. In relation to the hydrology routine seven natural stores are represented. These include snow storage, interception storage, from which evaporation takes place at the potential rate, the upper soil horizon, the lower soil horizon, transitional groundwater, groundwater and minor channel storage.

To gain an insight into the functioning of the model it is beneficial to take a more in-depth look at how these stores function and interact. Given the small amount of snowfall recorded in Ireland this store is not utilised. Interception storage represents the storage of moisture by the vegetation canopy. Evaporation accounts for losses from this store. Any moisture in excess of storage, determined by vegetation type, is passed on to the upper soil horizon. The upper soil horizon represents the moisture held in the upper (A) horizon or topsoil and has a finite storage capacity equal to the depth of the A horizon multiplied by its porosity. A limit on the rate at which moisture can enter the upper soil store is applied based on its potential infiltration rate. Losses are met by evaporation, interflow and percolation to the lower soil horizon. Evaporation is controlled by the forces of capillary suction, while interflow is a function of the effective horizontal permeability of the soil layer. The lower soil horizon represents moisture below the upper horizon but still within the rooting depth of vegetation. Again evaporation and interflow account for losses from this store as well as percolation to groundwater.

The transitional groundwater store is an infinite linear reservoir, which serves to represent the first stage of groundwater storage. This store has greatest importance in catchments with permeable geologies where many of the fissures and fractures holding moisture may interact with the stream channel rather than with deeper groundwater. Losses from this store are controlled by a discharge coefficient and by the proportion of the moisture leaving storage that enters the river channel. Groundwater is also represented as an infinite linear reservoir, assumed to have a constant discharge coefficient. Groundwater parameters include the groundwater recession rate, the proportion of the catchment with no groundwater, transitional recession, the proportion of the recession that is transitional and the ratio of groundwater to surface catchment. The most sensitive of the groundwater parameters is the groundwater recession rate, computed from observed flow by studying periods in a dry summer when little or no rain has fallen. The ratio of groundwater to surface catchment also shows a high sensitivity, its value being derived from the geological survey of Ireland's Aquifer map (GSI, 2003). The final conceptual store represented by HYSIM is minor channel storage. This component represents the routing of flows in minor streams and ditches.

4.0 MODEL CALIBRATION AND VALIDATION

Before running the model with the downscaled data, HYSIM was calibrated and validated on observed records. Daily precipitation and PE data were obtained from Met Éireann for a baseline period of forty years (1961-2000). Daily streamflow data for this period were obtained from the Office of Public Works (OPW). A split sample procedure was adopted for calibration and validation. The first thirty years of the baseline data set (1961-90) were used for calibration so that the model could be trained on as much variability in streamflow as possible. Validation was conducted for the period 1991-2000. This decade has been the warmest globally, with 1998 being the warmest year in the global instrumental record while in Ireland the warmest year was recorded in 1997. Furthermore, the ten years 1991-2000 have presented some of the largest flood peaks on record in Ireland, such as the November 2000 floods and thus provide a good test of model performance, with conditions being more akin to those expected under climate change than at any other period in the baseline data set.

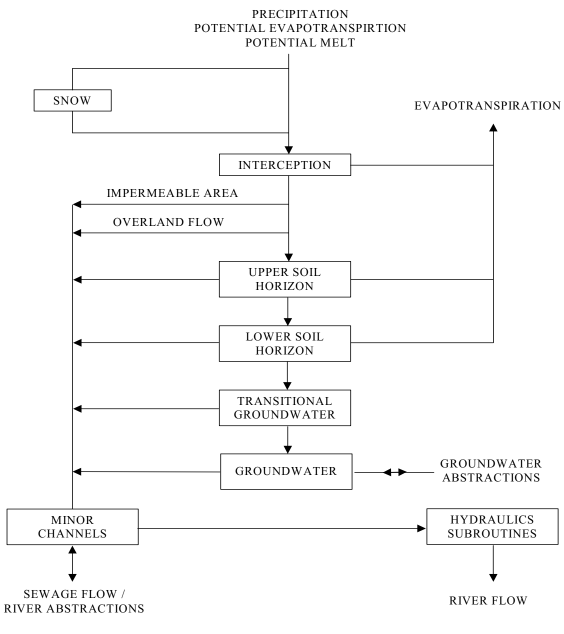

Figure 1: Hysim model structure

When assessing the impacts of climate change on water resources there is a cascade of uncertainty that begins when future socio-economic storylines are converted to future emissions scenarios and ends in impact modelling (Wilby, in press). While an analysis of uncertainty is beyond the scope of this paper, conceptual rainfall-runoff models are subject to a number of simplifications that give rise to uncertainty (e.g. Parameter uncertainty). In order to take account of this uncertainty one hundred parameter sets were generated for each catchment during the calibration period with each of these being validated for the 1990s.

In order to determine the degree of accuracy obtained during calibration and validation two 'goodness-of-fit' measures were employed, the Nash-Sutcliffe Efficiency Criterion (NS) and the Percent Bias (PBIAS). In terms of the entire calibration period results ranged from 0.73 to 0.86 for NS, with a value of 1 being indicative of a perfect fit, and from -1.81 to -1.11% in terms of PBIAS. Validation results ranged from 0.70 to 0.85 for NS while results ranging from 1.65 to 3.01 were obtained for PBIAS. Given that the validation period provides the closest surrogate possible for future conditions, the results achieved give increased confidence to the transference of parameter sets from current to changed climate conditions. However, there is the caveat that land use and soil textural characteristics will remain the same under a changed climate.

5.0 FUTURE SIMULATIONS

By forcing the rainfall-runoff model with the downscaled output from each GCM, simulations were produced for three future time periods (2020s, 2050s and 2080s). HYSIM was used to assess changes in streamflow as well as in upper soil, lower soil, transitional and groundwater storage. The remainder of this paper presents the output from HYSIM for each of theses time slices using downscaled data from the HADCM3 A2 scenario. The output for each time slice is compared with GCM control conditions (illustrative of the 1961-1990 period) and the percent change is calculated. The results shown represent the average response once uncertainty is taken into account. Seasons are classified as Winter (DJF), Spring (MAM), Summer (JJA) and Autumn (SON).

5.1 CHANGES IN MONTHLY FLOW REGIMES

Within the Boyne catchment monthly flow regimes tend to follow the general patterns of change in precipitation (Figure 2) with a lag of approximately two months. Evidence for this lag is also present between recorded precipitation and streamflow, indicating that the model represents catchment storage quite well (Figure 2). By 2020 the river Boyne experiences a decrease in streamflow for all months with a maximum decrease of approximately 20% in the late Summer and early Autumn. By 2050 there is an increase in winter streamflow corresponding to the increasing rainfall suggested for this period. Reductions in monthly average streamflow are evident for the summer and early autumn months. This trend continues into the 2080s with further increases in winter streamflow, especially in the months of February and March with increases of up to 45%. This increase in winter precipitation is seen to increase and sustain streamflow for the Spring months where-after there is rapid drying and reductions of up to 20% in streamflow for the summer and the majority of the Autumn period. The continued reduction in autumn streamflow demonstrates that low flow conditions may extend later in the year than currently experienced.

5.2 CHANGES IN SOIL STORAGE

The amount of water stored in the soil is fundamentally important to agriculture and has an influence on the rate of actual evaporation, groundwater recharge, and the generation of runoff (IPCC, 2001). Gregory *et al.* (1997) show with the HadCM2 GCM that a rise in greenhouse gas (GHG) concentrations is associated with reduced soil moisture in Northern Hemisphere mid-latitude summers. The local effects of climate change on soil moisture, however, will vary not only with the degree of climate change but also with soil characteristics. The water-holding capacity of soil will affect possible changes in soil moisture deficits; the lower the capacity, the greater the sensitivity to climate change (IPCC, 2001). Both soil horizons within the Boyne catchment are characterised as having a loamy texture; classed as an "intermediate" soil between sands and clays, composed of many different sized soil particles that combine fertility and moisture-holding capacity with good drainage (Gardiner and Radford, 1980). In terms of the upper soil there is a decrease in storage for almost every month by the 2020s, the greatest decrease again being in late summer and autumn (Figure 2). This trend is continued for the 2050s but with greater reductions extending into spring as a result of decreases in precipitation. By 2080 the largest changes are seen in the summer months with reductions of 30% in the month of August. Again reductions are shown to extended into the autumn months. Over the range of time slices considered changes in upper soil storage are consistently negative, even in winter months for the 2080s where an increase in precipitation is evident. This may be due to the fact that effective rainfall is compensating in other stores. Such reductions may have large consequences for vegetation and agriculture.

The response of lower soil storage (Figure 3) is similar to upper soil storage. By the 2020s all months show a reduction of up to 6%. By the 2050s slight increases are evident for the Winter months but the extent of the decrease is greater for the remainder of the year. The 2080s show a continued exaggeration of this trend with continued decreases being experienced during the Summer and Autumn and continuing right into the Winter. Greatest decreases, in the order of 20% are evident for the months August, September and October. Under present conditions this part of the year is important for recharge purposes and significant reductions here could have a knock on effect on storage in other months. There is a degree of uncertainty associated with future simulations of soil storage as climate change also may affect soil characteristics, perhaps through changes in water logging or cracking, which in turn are likely to affect soil moisture storage properties. Furthermore, changes in land use may alter the amount of evapotranspiration accounting for losses from this store.

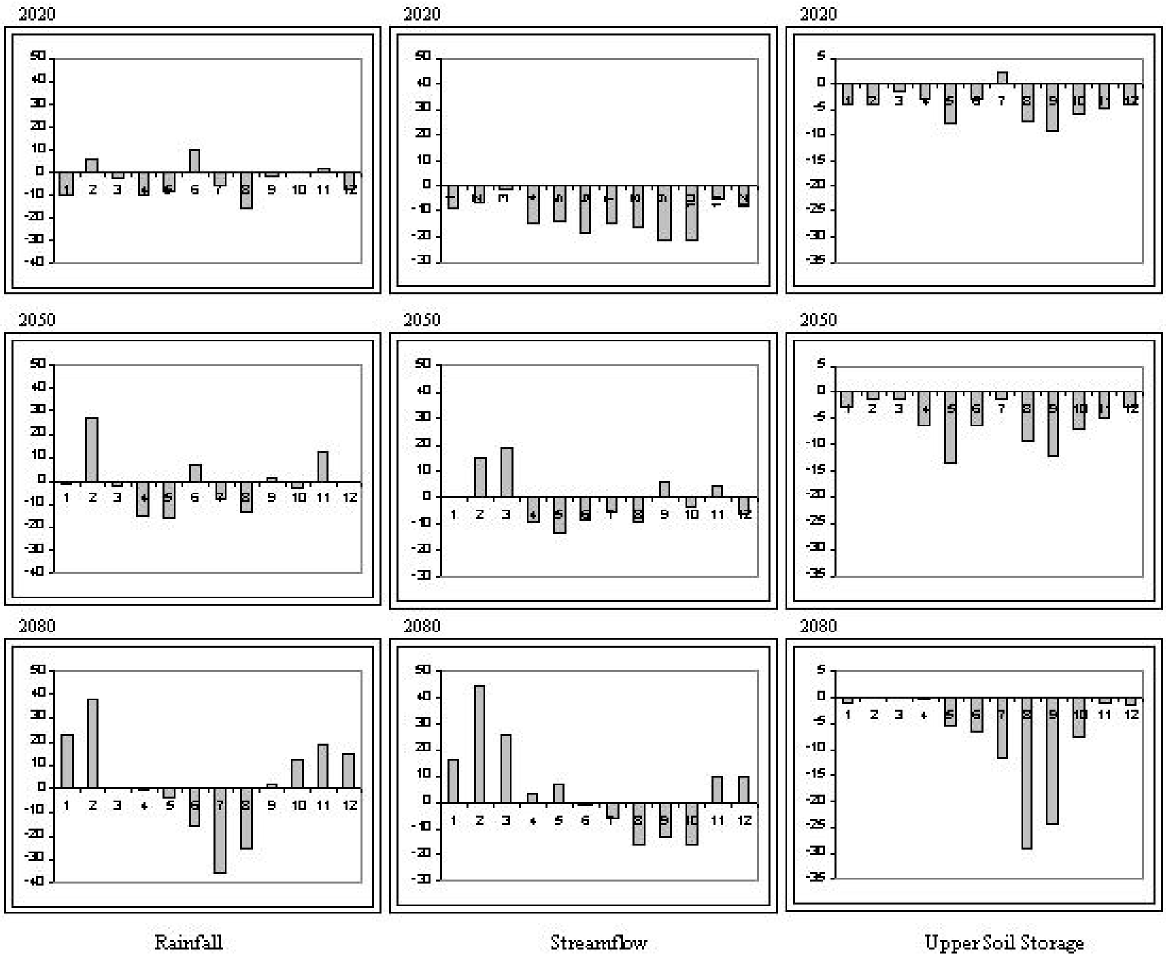

Figure 2: Percent change in monthly rainfall (left), streamflow (centre) and upper soil storage (right) for each future time slice.

5.3 CHANGES IN GROUNDWATER STORAGE

Groundwater storage is an important natural resource with about 20-25% of freshwater supplies in Ireland being derived from this source (Daly & Warren, 1998). However, relatively little research has been conducted on the effects of climate change on groundwater supplies. Increased winter rainfall—as projected under most scenarios for mid-latitudes—is likely to result in increased groundwater recharge (IPCC, 2001). However, as has been shown for the Boyne, soil moisture deficits tend to commence earlier in Spring and persist later into the Autumn, thus having the potential of offsetting the amount of effective rainfall available for groundwater recharge. Such changes are also capable of altering the timing and duration of the recharge period. As with changes in soil storage, changes in groundwater storage due to anthropogenic climate change for a particular catchment are largely dependent on individual catchment characteristics and the type of aquifer under consideration. The Boyne catchment is predominantly underlain with impure limestones interspersed with sandstones, shales and undifferentiated sedimentary strata (EPA, 2004). There are few regionally important aquifers within the Boyne catchment due to the unbedded nature of the underlying limestone. However a large proportion of the catchment is underlain with locally important aquifers (approximately 67%)

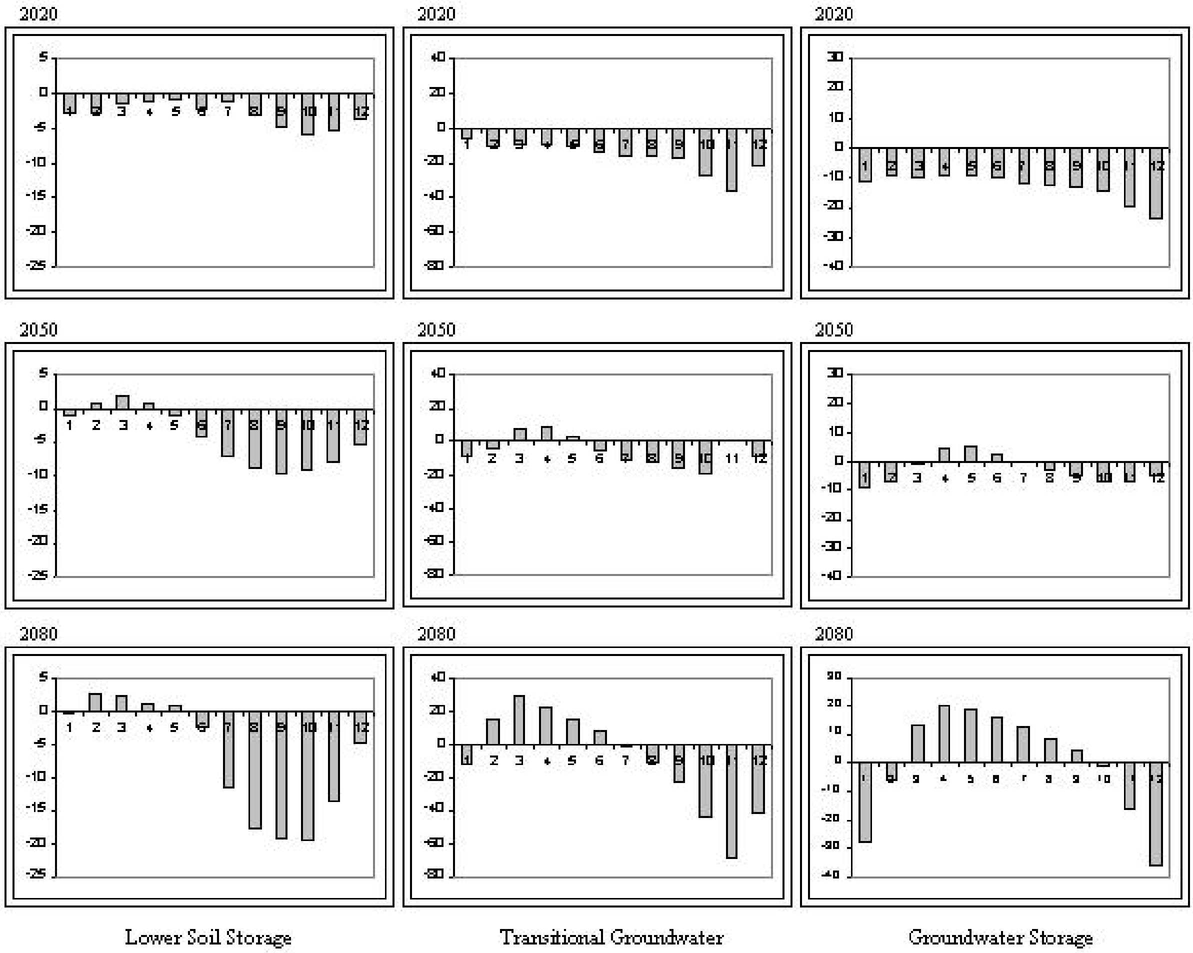

Figure 3: Percent change in monthly lower soil storage (left), transitional groundwater storage (centre) and groundwater storage (left) for each future time slice

Known locally important sand and gravel aquifers of glacial origin within the catchment have been shown to have a rather low transmissivity (EPA, 2004). The transitional groundwater store serves to represent the first stage of groundwater storage. By the 2020s there is a reduction in transitional groundwater storage in all months, largest in the autumn with reductions of up to 40% in November (Figure 3). These reductions are reduced by 2050 due to short-term increases in summer and autumn precipitation. Slight increases in storage are also evident during the spring. This increasing trend in Spring storage is extended to the 2080s with increases in storage developing into the early Summer. However, most evident by the 2080s are the large reductions in transitional groundwater storage during the late summer, autumn and winter seasons. Indeed, it is the winter decrease in storage that is most prominent, with a reduction of over 70% in November. This decrease in winter storage exists even though increases in precipitation of up to 20% and 30% are projected for autumn and winter respectively by the 2080s. This again highlights the potential that changes in the timing, duration and extent of soil moisture deficits can have in offsetting the amount of effective rainfall available for groundwater recharge.

Groundwater storage is seen to reduce in all months by the 2020s with the largest decreases coming in autumn and winter, as stores are not being recharged (Figure 3). The greatest reduction is shown for December with a decrease of approximately 24% from current levels. This decrease is reduced by the 2050s, again due to the short-term increase in summer and autumn precipitation while April, May and June begin to see increases in groundwater storage. By the 2080s dramatic changes in groundwater storage become evident. Increases of up to 20% are evident for spring months while summer and early autumn also experience an increase, although this increase diminishes over time. The largest reductions in groundwater storage are evident in November as well as throughout the Winter period with decreases of as much as 35% in December groundwater storage. When changes in groundwater storage for the 2080s are compared with the percent change in rainfall for the same period a distinct lag is evident. It would seem that increases in precipitation during the autumn do not replenish groundwater stocks until spring. This may be due to the combination of increased deficits in soil storage offsetting increases in effective rainfall, as well as the poor transmissivity of the sand and gravel aquifers. On the other hand, increases in winter precipitation tend to supplement groundwater storage throughout the spring and summer. This characteristic is also evident in streamflow during the summer months where baseflow is critical in sustaining discharge.

6.0 CONCLUSION

Changes in Irish climate as a result of anthropogenic climate change are likely to have a significant impact on water resources. Such impacts have the potential to alter each element within the catchment water balance. Impact assessments are subject to uncertainty derived from emission scenario, Global Climate Model (GCM), downscaling technique as well as uncertainties derived from the impact model employed. This work uses statistically downscaled data from three GCMs using two emission scenarios. Rainfall-runoff model uncertainty is catered for and the presented results are based on the average changes. Given the preliminary nature of this work only output from one GCM using the A2 medium-high emission scenario for one catchment is presented. From this analysis it is evident that increases of precipitation in autumn and winter will be critical in sustaining water resources in the Boyne Catchment. The failure of precipitation in these months may mean that important stores are not replenished resulting in an increased risk of drought throughout the summer months.

7.0 ACKNOWLEDGEMENTS

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Session III

New Tools and Practical Examples I

MODERN GROUNDWATER EQUIPMENT – EXAMPLES OF USE AND RESULTS

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1.0 INTRODUCTION

Hydrogeology is based on an understanding of the subsurface, which, in simple terms, consists of two very different components; a static framework of solid material (rock or soils), and the movement of a very mobile fluid (water). Gaining an understanding of the rock and the water components of a project or problem is the fundamental objective of every hydrogeologist.

The following joint paper aims to illustrate the considerable contribution made to modern hydrogeology by recent advances in field equipment. Many readers may have had their own experiences with the new equipment. The purpose of the paper is to share a diversity of recent experience from three field hydrogeologists, and provide an update for those who have not, so far, had a chance to use the equipment.

Groundwater moves from places where the water table level, or confined water pressure, is relatively high, to places where the level or pressure is relatively low. In effect 'groundwater flows downhill'. This simple understanding is the basis of much of hydrogeology. It is very important because, unlike surface water, it is not possible to see groundwater flowing, nor is it possible to directly measure it flowing. Therefore hydrogeologists need to excavate into the subsurface and measure water levels in order to understand, predict and monitor groundwater flow. Groundwater flow is relatively slow, and with rare exceptions flow cannot be seen. Instead measurements underground are usually water levels which indicate that there is a potential for flow. Potential for flow does not mean that flow necessarily takes place. When potential for flow becomes apparent, it becomes necessary to understand the nature of the static framework of rocks or overburden that might permit, or conversely, inhibit this potential for flow to be realised. Rocks can be observed where they outcrop at the surface, or from cuttings or cores obtained whilst excavating the subsurface. Rocks and soils change spatially, but they do not change significantly with time. Whereas water is always moving, however slowly. Time is therefore the fourth dimension in space, that hydrogeologists have to take into account. Water enters the ground at certain times of the year and water is always discharging from the ground into rivers, streams lakes or the sea. There is therefore a groundwater system that changes in space and time, and to monitor and understand this system, it is essential that hydrogeologists should be able to measure water levels accurately and frequently.

2.0 DAVID BALL'S CONTRIBUTION

The first groundwater field work that I carried out was on the King's River catchment in Co. Kilkenny in 1972. In order to measure static and pumping water levels in existing boreholes I used sound. I, and the Geological Survey, did not have the money to buy an electric water level contact tape. Instead we improvised on an old 'sounding line principle of a weight, a line and a tape measure. For a weight I used a Rawlplug handle which was a slim hexagonal heavy piece of forged steel with a hole through it. The Rawlplug handle was Eugene Daly's idea, because it was small, slim, and heavy, and when lost in a borehole could be easily replaced at a local hardware store. A nylon fishing line was attached and the Rawlplug handle lowered into the hole with an up and down 'jiggling motion'. When the weight struck the water surface there would be a plop or splashing sound that carried up the borehole to my, straining, ears at the surface. A knot was tied in the line and the whole assembly dragged out of the hole to the nearest piece of flat ground. The line was tensioned and the distance between the tip of the Rawlplug handle and the knot measured with a surveyor's tape. This was the way I measured water levels 30 years ago, and as you can appreciate, it was inaccurate, and time consuming. Bear this in mind when using early 1970's water level data, and imagine the difficulty in measuring (listening to) rapidly falling water levels in a pumping borehole next to a large shed full of battery chickens.

I still call modern electric contact water level measuring tapes 'sounding lines'.

A robust, professional sounding line subsequently became the basic tool of a working hydrogeologist. The better examples enabled water levels to be measured to an accuracy of 0.5cm at frequent intervals during pumping tests, but even so it was rarely possible to measure and record data by hand at intervals less than 15 seconds. The only alternative was an expensive autographic pen, chart, float and counterweight recorder. These could give a continuous analogue record of water level changes, provided the pen worked, the chart and wire scales were accurately prejudged and the float did not get stuck. Another method was to use a manometer on an air pressure line with an open end below the water level. It was possible to measure the pressure of water above the end of the line. Trying to keep a constant flow of air out of the end of the airline with a tyre pump whilst at the same time recording the movement of a needle on a manometer dial was an unsatisfying experience that I had twice.

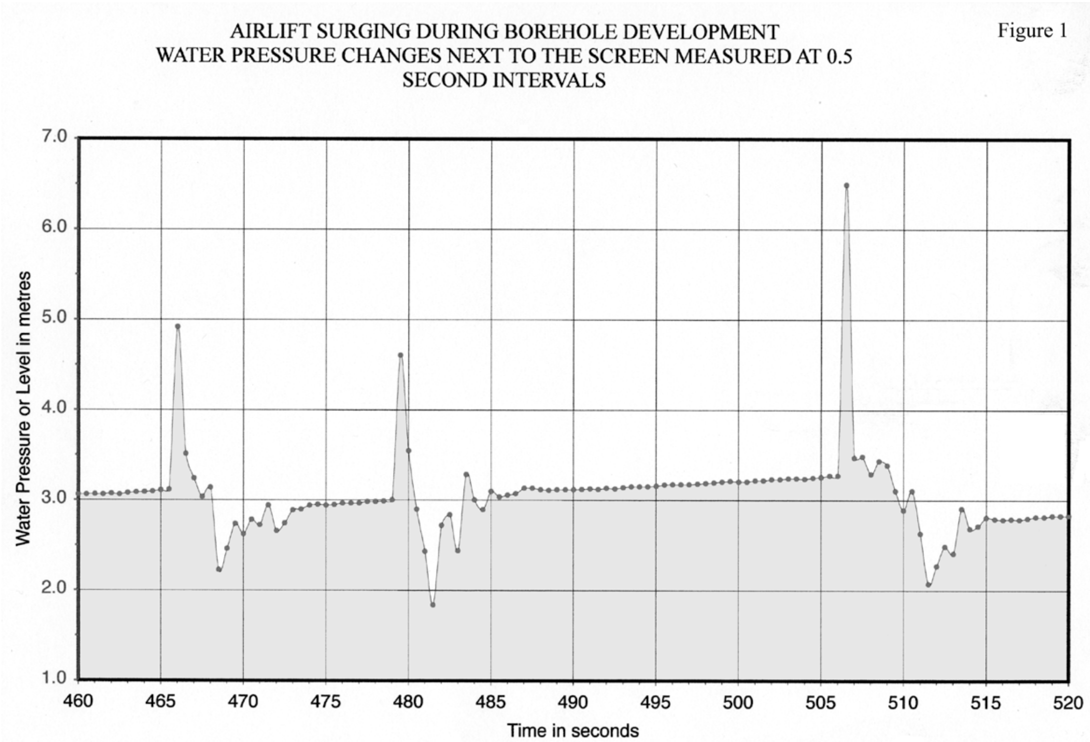
Large scale pumping tests involving many satellite observation boreholes often involved many staff and considerable organisation and expense. I ran a test in Darfur in 1976 that involved 10 people running a relay race with two sounding lines, and Phil Lamoreaux (past President of IAH) once described a major test in the Florida karst limestones that involved a helicopter, walkie talkies, countless staff, generators, cars and caravans that cost $2 million in the 1980's.

New Equipment and examples of diverse uses and better data.

The big revolution in the work of a hydrogeologist has been the advent of pressure transducers and micro-data loggers and lap top computers. It has recently become possible to place an accurate pressure transducer in a small robust device that can record and store changes in water pressure and temperature at frequent intervals over a long period of time. Those of you who have had to drag yourself out of a warm bed at 4am for the third winter's night in a row, to take manual measurements during a long pumping test, will appreciate the full significance of the last statement.

The latest pressure transducer water level loggers are smaller and less expensive. They have a memory capacity of around 24,000 readings, batteries that are claimed to last for 9 years, and can be programmed to take readings at intervals ranging from 0.5 second to 99 days. They also have an optional sampling rate that varies over time, so that for example they will take readings every 0.5 seconds in the early stages of a pumping test when water levels are falling rapidly to readings every 20 minutes after a week of pumping.

These latest water level loggers enable the modern hydrogeologist to accurately measure changes at short time intervals that were previously impossible. For example when airlift surging a borehole to loosen fine grained material around the well screen and develop a higher permeability natural gravel pack, we want to try to maximise the oscillation in pressure across the screen slots. In the past we used an empirical method to determine the best time to release a surge of air and the duration of the surge. Now, with the aid of modern loggers we can put the instrument in the bottom of the hole or next to a particular part of the screen and measure pressure at short intervals. We can try out a variety of surge patterns and then retrieve the logger, download the data, and choose the pattern that appears to provide the best pressure oscillations across the screen. Figure 1 shows field results from a borehole during airlift surging. Notice the time scale on the X axis and the frequency of measurements.



Pumping tests and aquifer tests (where measurements are made in the pumping borehole and observation boreholes at a variety of distances away) are a basic field procedure in hydrogeology. These tests should be carried out in a systematic and controlled manner. The new equipment not only provides better data but also makes it easier for a single person to carry out a test on one or more boreholes. It was usual for one or two things to go wrong or require adjustment in the early part of the test when water levels are falling quickly. In the past, when water levels were measured manually, these emergencies usually meant that there were enforced breaks in the water levels measurements. The modern equipment frees up the hydrogeologist. I estimate that the modern data loggers have reduced supervision and data collection time by about 90%. Figure 2 gives an example of the quality of data obtained during a long constant discharge test and partial recovery on a high yielding exploration borehole.

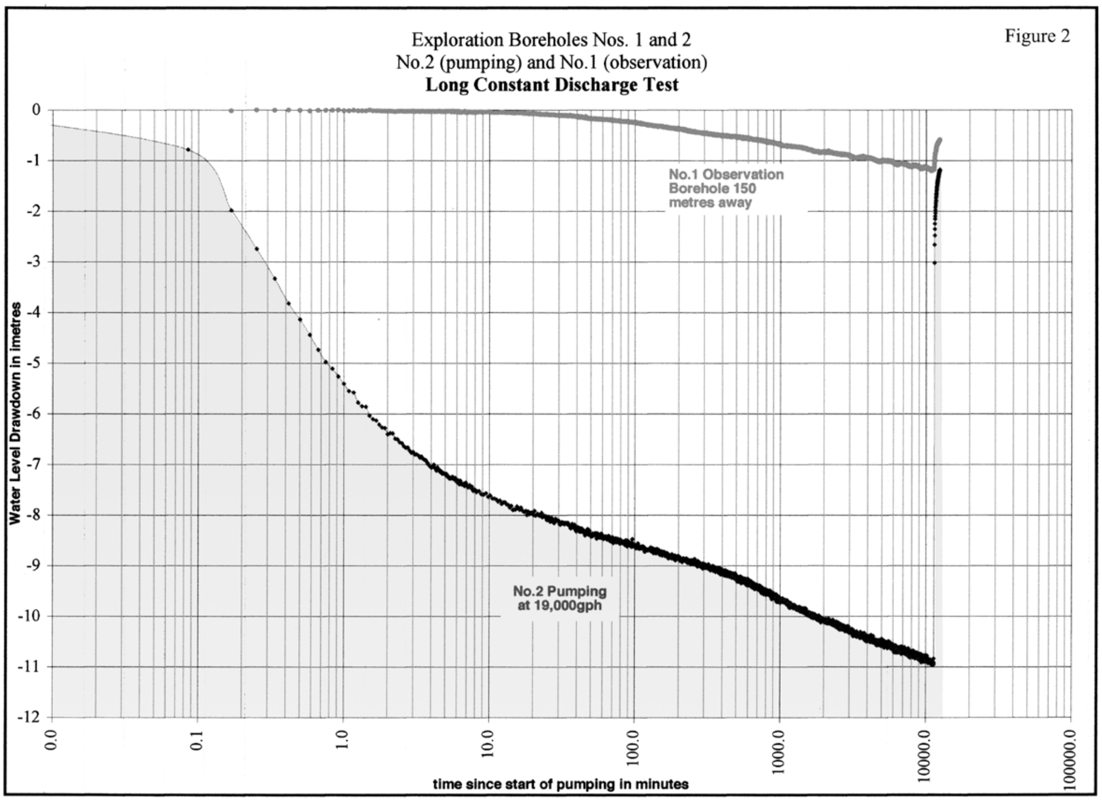
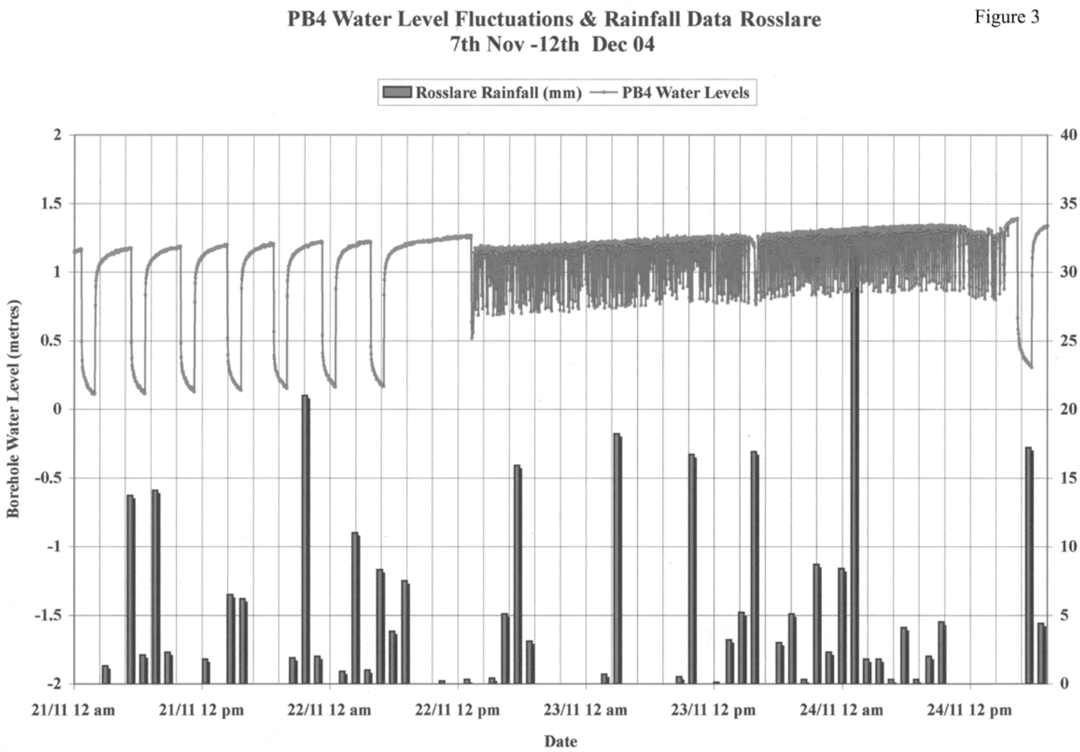


Figure 3 is an example of the rise and fall in water levels in a borehole used as supply for a hotel golf club and housing. The demand for water should be low and fairly predictable in the November-December period. A high quality pump was installed in September 2004, but by January this year the bearings at the base of the motor had failed. Fortunately a water level logger had been monitoring the cycle of pumping drawdown and recovery. Figure 3 shows that an electrician and plumber had changed the pump controls and altered valves just after lunch on the 22 November.



Instead of pumping into a reservoir with a float switch on a fixed time basis, they had directed the pump output straight into the rising main to the houses, hotel and club house without a pressure balancing tank. Every time the pressure fell in the main the pump switched on, and then rapidly switched off. The pump turned on almost every time someone filled a kettle or flushed a toilet. The data shown in figure 3 could not have been collected manually. These data were used to show that the pump failure was the client's responsibility and not the pump manufacturers or the consultants.

Last year I drilled a series of holes through coastal sand dunes, down through a layer of till into a previously unrecognised, karst limestone aquifer. Modern water level loggers can be used to accurately measure the response of groundwater systems to tidal fluctuations. Figure 4 shows a comparison of water level fluctuations in the sea and in the limestone aquifer over a spring tide cycle.

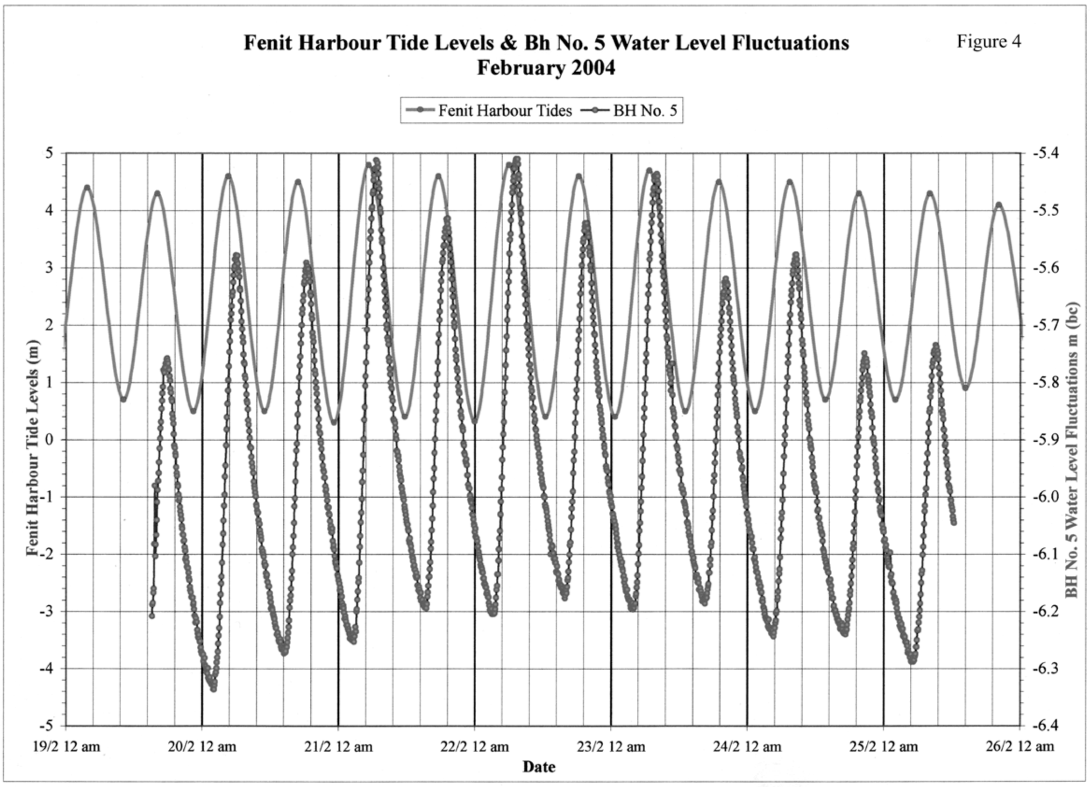
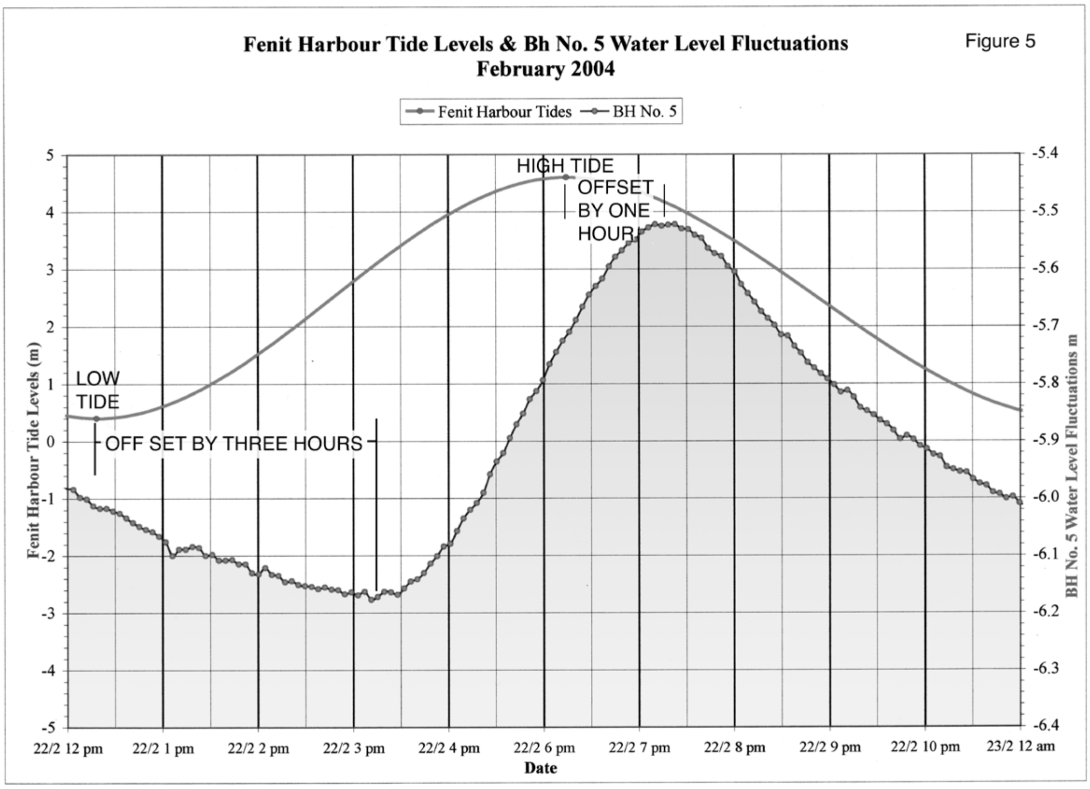


Figure 5 shows an enlargement of one tide cycle. The water levels in the aquifer carry on falling even though the tide is rising, yet the water levels in the aquifer start falling shortly after the high tide has turned. This shows that the limestone aquifer is not confined, and indicated (when we first observed the data) that sea water was entering and leaving the aquifer laterally through a portal at some level above the low tide level. We search the adjacent beaches at low tide and found springs from a sand covered limestone outcrop midway up the beach.



The early data encouraged us to obtain a modern logger that could also measure water levels, temperature and electrical conductivity (salinity). Figure 6 shows marine tides, and water levels and salinity in the aquifer. It is immediately apparent that sea water does enter and leave the aquifer. This is very pronounced during the spring tides, but is only slight during the neap tides.

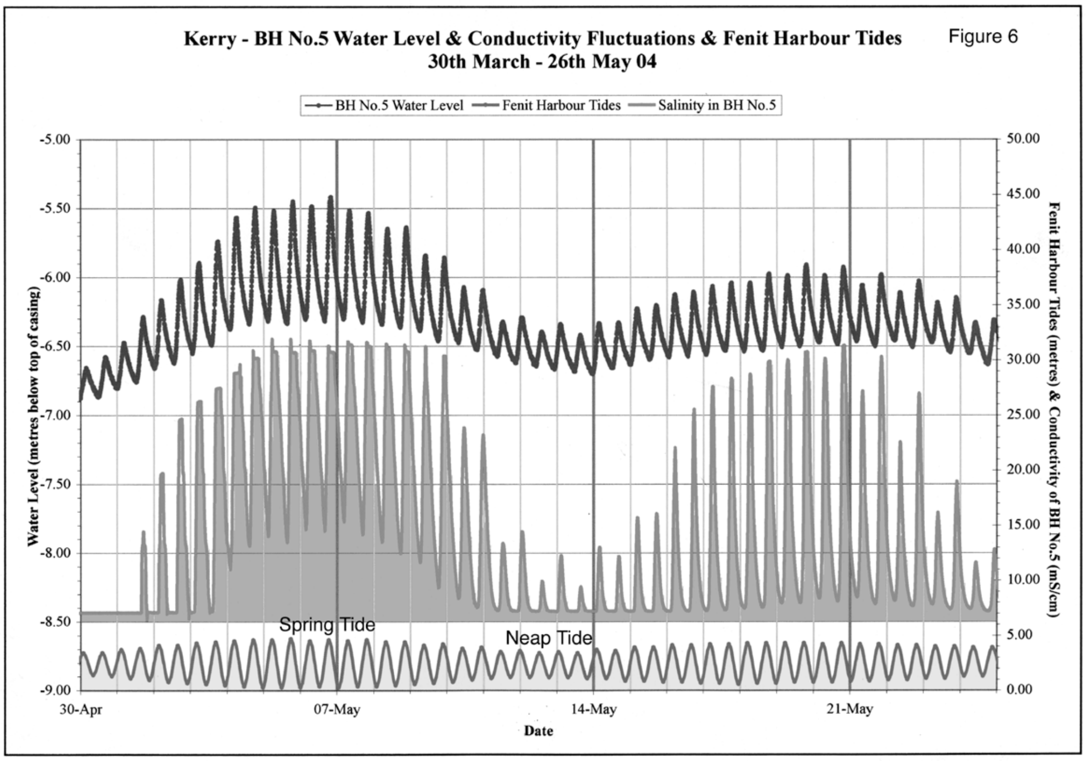
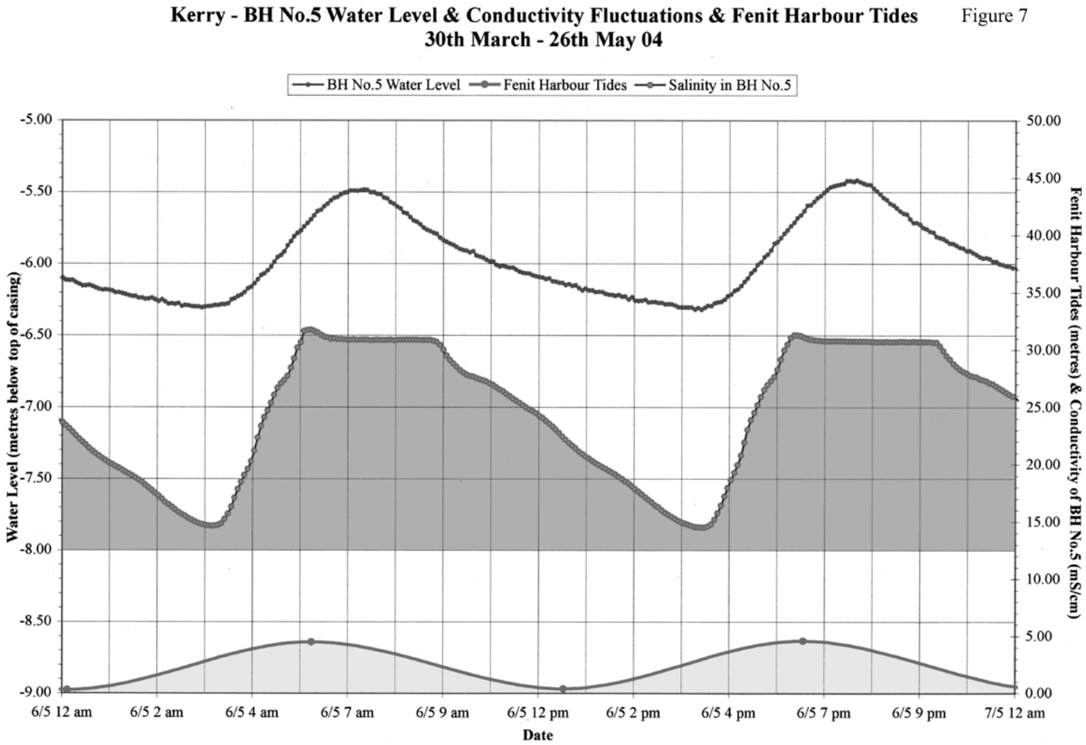


Figure 7 is an enlargement of two tide cycles. It clearly shows the sea water entering the aquifer as soon as the marine tide reaches the spring entrances. The salinity climbs from 15,000 µS/cm to over 30,000 µS/cm. Curiously, after a short peak the salinity stays constant until the middle of the tidal retreat, and only then begins to fall. These data indicate that the karst conduits contain a brackish water, and that pure seawater does not reach the borehole some 100 metres inland. This brackish water is like a mixing zone that moves backwards and forwards from the shore with each tide. This mixed water probably does not ever completely leave the aquifer.



It can be seen that the modern water level, temperature and conductivity loggers enable hydrogeologists to obtain a wealth of new, reliable and accurate information in order to be able to understand changes with time in aquifers. The wealth of information is challenging our conceptual understanding of groundwater flow systems. With the new equipment we are able to push the boundaries of our understanding. We also spend fewer sleepless nights gathering data.

3.0 PATRICK LAFFLY'S CONTRIBUTION

The use of Compensated pressure transducer data loggers, laptop computers and analysis software during pumping tests

3.1 INTRODUCTION

Hydrogeologists are able to utilise a combination of modern equipment to monitor and analyse the progress of a pumping test without interrupting the collection of data. This can be done by using a surface mounted pressure transducer and data logger that records the pressure needed to evacuate an airline below the water level, and also compensates for atmospheric air pressure. This compensated data equates to a water level above the end of the airline, which can in turn be converted into a water level below the initial static water level at the beginning of the test. A laptop computer with an infrared communication system can be used to download the data from the logger during the test without interfering with the collection of data. Modern software on the lap top can be used to carry out an analysis of the data during the test in order to monitor the interim response of the aquifer to pumping.

An example of a compensated pressure transducer data logger is the Orphimedes instrument which can be used to measure surface water or groundwater levels. The instrument uses the bubble principle. A pump generates compressed air which flows through a bubble chamber where it bubbles out into the water.

Orphimedes are specially designed for continuous monitoring of water levels over long periods of time. The minimum recording time interval is 5 minutes. The maximum measurable drawdown is 10m. The early drawdown and recovery data during a pumping test has to be recorded at a much shorter time intervals, and a drawdown of 10m is often exceeded in the pumping well. Therefore this instrument is not usually appropriate for measuring water levels in a pumping well, but it has been found that it may be used to record water levels from monitoring wells which are distant from the pumping well, where the response is slower and the drawdown is less.

3.2 EXAMPLE OF USE: 72-HOUR PUMPING TEST

The following example illustrates the use of a compensated pressure transducer for the design of a dewatering project in a limestone aquifer where 9 monitoring wells were installed at the site. A step test and a 72-hour constant rate test were carried out. The purpose of the aquifer tests were to:

- calculate the quantity of water that would have to be pumped to maintain dry working conditions at the site;
- predict the drawdown generated by dewatering at various distances from the site; and,
- evaluate the impact on the groundwater regime.

3.3 INSTALLATION

The compensated pressure transducers were delivered to the site on the day before the pumping test commenced. Having no experience with equipment , a long day on site was necessary to install and programme all the dataloggers (5 no. in total). After finding the best way to proceed, the average time to install and programme one instrument was one hour. Securing the instrument at the top of the well and calculating the length of cable necessary was found to be the most time consuming part of the installation process. When the instrument was installed in the well a laptop computer was used to programme the measuring interval. Programming the instrument was completed via Infrared. A sharp knife was the only necessary tool to install the compensated pressure transducer in the monitoring well.

3.4 EXAMPLE OF RESULTS

Five monitoring wells were equipped with data loggers. Water levels from the four other wells on site, and from the pumping well were recorded manually using a dipmeter. Figure 8 shows an example of data recorded by a compensated pressure transducer in BH07 (Borehole 07), which is located 100m from the pumping well. After termination of the pumping test (after 72 hours), monitoring of the observation wells continued. It was found that after 4 days none of the observation wells monitored during the pumping test had recovered to their pre-test static water level. All observation wells exhibited a similar pattern. No other pumping was taking place in the area. This type of recovery data was therefore indicative of a limited aquifer. Figure 8 also indicates a change in pumping rate (left part of the graph). Changes in pumping rate distort pumping test data and automatic recording of water levels by the datalogger at small intervals was useful to identify precisely which data could be used for the pumping test analysis and interpretation.

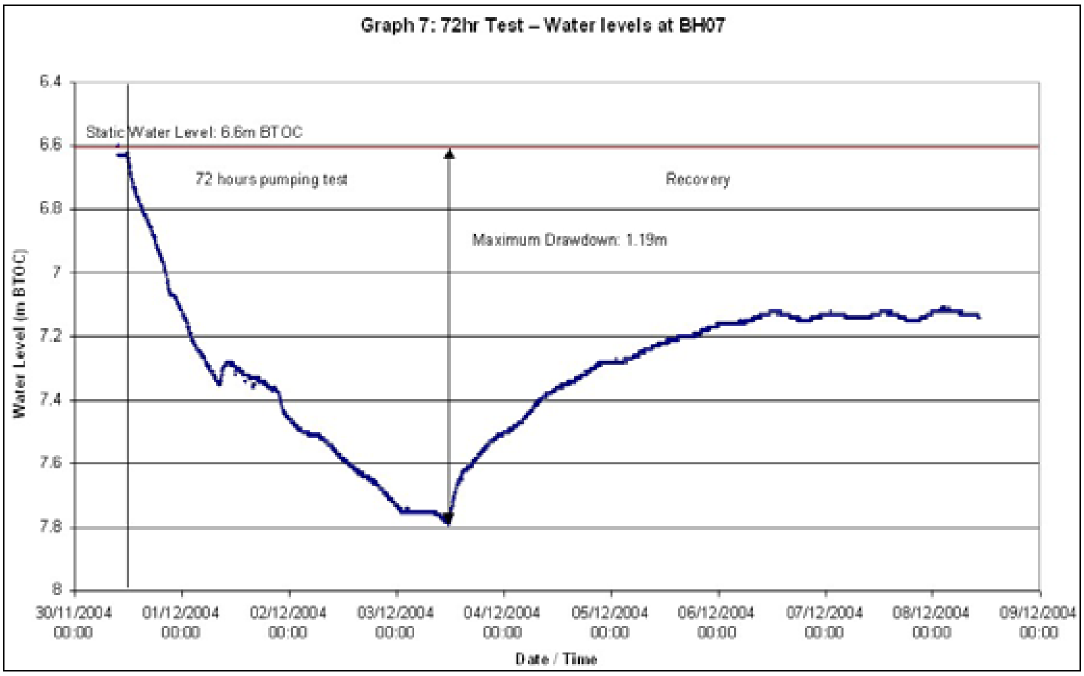


Figure 8: Water level at BH07 (100m from pumping well)

Several techniques were used to analyse the hydraulic response of the aquifer during the pumping test. Figure 9 and Figure 10 show Cooper-Jacob plots for BH04 and BH07 respectively. BH04 is located 10m from the pumping well and levels were recorded manually due to the significant drawdown anticipated in this well. Both graphics show a sudden increase of drawdown and suggest the presence of a hydraulic barrier. The Cooper-Jacob analyses of drawdown data from both observation wells (BH04 and BH07) gave a similar (same order of magnitude) permeability value (K value) for the aquifer.

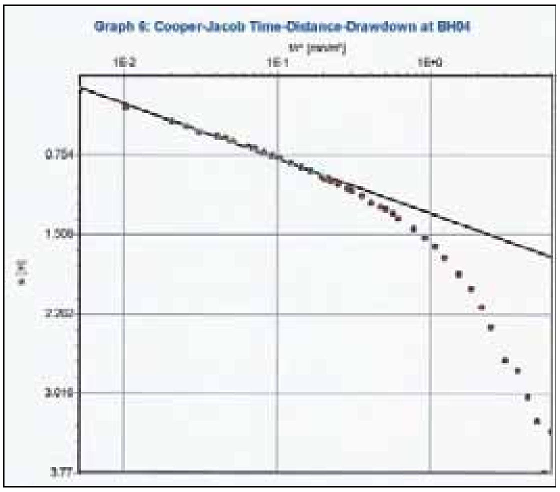


Figure 9: Cooper Jacob plot – BH04

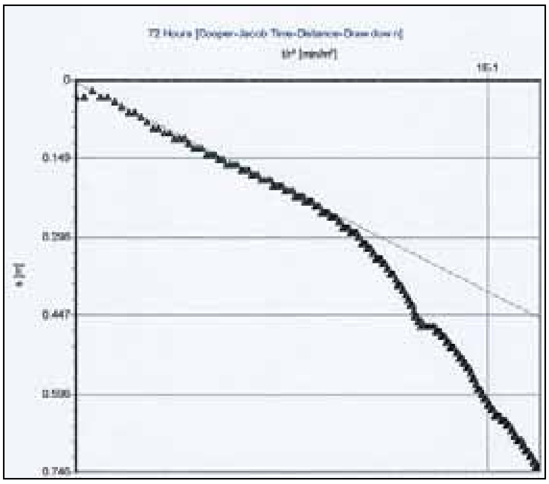


Figure 10: Cooper Jacob plot – BH07

3.5 COMMENTS

For this test, compensated pressure transducers were programmed to measure water levels at 5-minutes intervals. Water level data from the observation wells were used to calculate aquifer parameters and the results were very similar to those calculated from analysis using the manually measured data. They were also useful to identify changes in pumping rate and select the data to be used for the pumping test analysis. The use of the compensated pressure transducer allowed downloading of water level data from observation wells at any time during the pumping test using a laptop and an infrared link. Using these data it was possible to complete on-site analysis and interpretation of the pumping test data using the laptop and Aquifer Test software.

Using a water level logging system like this during a pumping test allows the hydrogeologist the freedom, and time, to interpret collected data, to leave the site, or to monitor other observation wells manually which he/she otherwise would not have had the time to do, especially in the early stages of a test when monitoring frequencies are high.

4.0 MICHAEL GILL'S CONTRIBUTION

While I do not have the wealth of experience that David has (I started working on wetlands/ groundwater projects in 1996), I have managed to use a number of similar monitoring devices to gather groundwater and surface water data over the last 9 years.

When I started out in 1996, I was given a 5 m sounding tape by my good friend and colleague Jan Strefkerk (A Dutch Geohydrologist working with Staatsbosbeheer, The Dutch Forestry Service). The difference between my sounding line and David's 1970s sounding line was that mine was graduated, so measurements were easy to take. Although I can definitely appreciate the difficulty of hearing the 'plop', especially when dipping deeper wider diameter boreholes.

Much of my early work involved dipping the array of dipwells and piezometers that were installed at Raheenmore bog and Clara bog (Co. Offaly). Gathering groundwater and surface water data over seasonal cycles to generate water balances, and assess conservation measures at the two bogs was time consuming and involved many long hours hiking across saturated bog surfaces to dip remote wells/piezometers. Monitoring was completed on a fortnightly basis over two years. I was none the wiser and headed off, sounding line and notebook in hand, eager to explore and willing to walk and walk. Every now and then, the monotony of hiking would be broken by a frightened snipe or startled hare. Sometimes the weather was good and monitoring was easy, however in winter the weather was usually terrible and monitoring trips were difficult and cold.

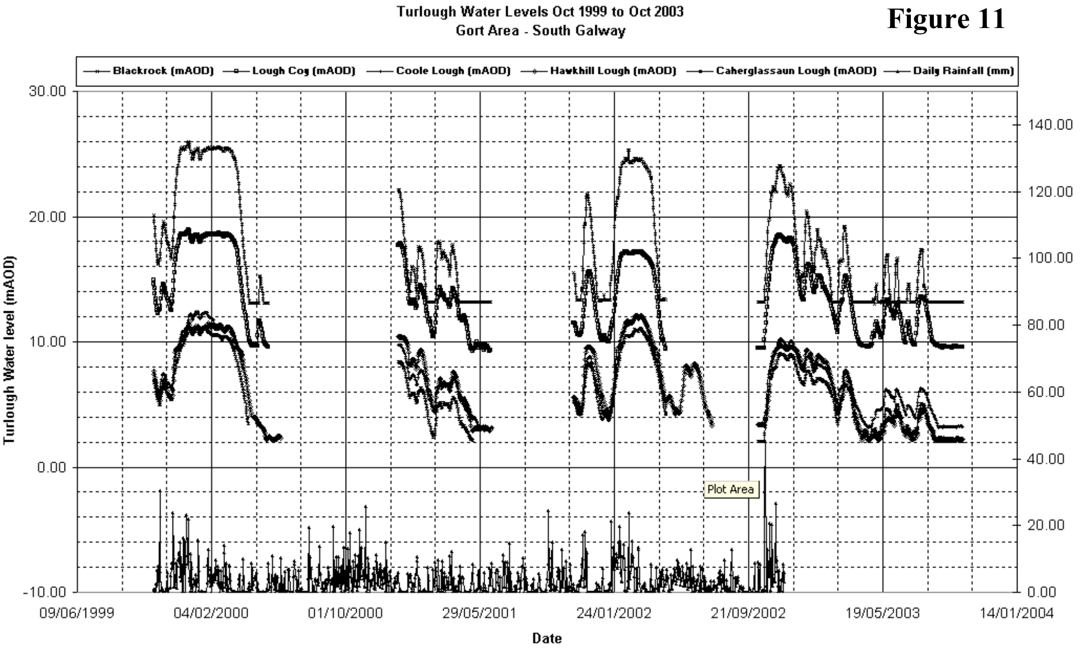
Thinking back, using some of the latest electronic devices, such as modern pressure transducers and GPS surveying equipment, which I use regularly now, would have saved me lots of time and hardship if they were available, or if I had known they were available. Now we're not talking about 30 years ago and some of the automatic equipment I use now to monitor water levels existed in 1996. If I had used them then, the data I would have gathered would have been continuous and the efforts I went to gather fortnightly data would have been more tolerable.

In early 1999, after a couple of years 'down the bog', Paul Johnston (Trinity College) and I set about implementing a monitoring programme on some of the major turloughs in south county Galway. This monitoring work was intended to be a continuation of turlough monitoring completed during the South Galway Flood Study.

Experience from the South Galway Flood Study suggested that pressure transducers with cables connected to dataloggers were difficult to install and maintain, as the dataloggers had to be above the highest expected water level and data cables between the transducer and the datalogger were sometimes up to 200 or 300 m long. This lead to problems with condensation in air lines between the transducer and the dataloggers which resulted in some spurious data. It was also difficult to bury cables in turloughs where overburden was thin or absent in places, and where inquisitive cattle displayed a fondness for cable chewing. In addition to these problems, the range of water level fluctuation in the turloughs we were required to monitor was from 0 (dry conditions) up to 13.5 m (approximate high water depth at Turloughnacloghdoo, or Blackrock turlough).

We tried a few different options and finally chose to use stand-alone pressure transducers with built in dataloggers. The beauty of these devices was that they were robust, compact, had varying monitoring ranges and they were almost cow proof. After deciding on the equipment, we had to come up with an installation technique that was flexible enough to allow data download during low and high flood conditions. To do this we secured the transducer/datalogger inside a 300 mm high section of 100 mm diameter thermoplastic Wavin pipe using cable-ties. The section of Wavin pipe was attached to a square (approx. 600 mm square) concrete paving slab using L-brackets. A hole was drilled in the centre of the concrete slab and a 10-15 m length of rope was fed through and knotted below the base of the slab. The concrete slab was intended to act as a positioning weight and the upright Wavin pipe was intended to protect the datalogger from seasonal silting up in the base of turloughs and from interference by farm animals during periods of low or absent water. A floating buoy was tied to the other end of the rope, and this was intended to act as a visual locating device during high water levels. The system was designed so that the loggers can be placed and retrieved during high or low water levels. During high water level periods the system can be installed by lowering the slab, the logger and the float from a small boat. During low water levels the system can be placed at the centre of the turlough on foot. We still use the same installation technique today as we did in 1999. Figure 11 shows some of the data that we have gathered at Blackrock Turlough, Coy Lough, Coole Lough, Hawkhill Turlough, and Caharglassaun Lough since 1999.

Figure 11



The transducer/dataloggers system I have used measures total pressure (water pressure + atmospheric pressure). Atmospheric pressure readings are therefore required to determine the actual depth of water above the transducer. An atmospheric pressure datalogger was installed close to Blackrock turlough and has been monitoring atmospheric pressure since November 1999. The transducer/datalogger in the base of the turlough outputs a total pressure graph. The atmospheric pressure readings for a given monitoring period are subtracted from the total pressure graph to give a turlough water level hydrograph relative to the base of the turlough.

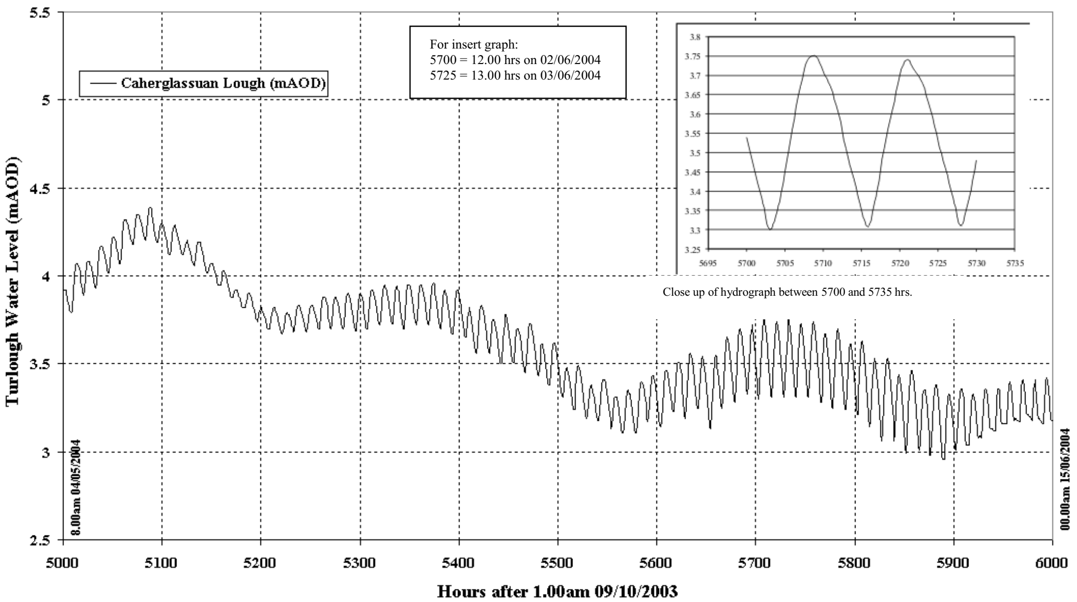
Using small monitoring frequencies has allowed us to identify some tidal influences in a number of the turloughs in South Galway, most notably in Caherglassaun Lough and Hawkhill Turlough. While others (Robert Lloyd Praeger and Bob Aldwell) have noted the influence of the tides in Galway Bay on water levels in inland turloughs (Caherglassuan is 5.5 km and Hawkhill is 8.5 km from Kinvarra), we don’t think that long term monitoring of this phenomena has been completed before. Figure 12 shows a hydrograph from Caherglassaun Lough from Summer 2004. The base of Caherglassaun Lough is 2.1 mAOD. Low lying sinkholes in Garryland and Coole Lough are also likely to display similar variations in water level as a result of tidal fluctuations in Galway Bay, however no monitoring has been completed at these sites. The small variations are probably a result of back-up of groundwater during high tide, and release during low tide, of groundwater in the karst conduit systems which discharge into Galway Bay from Caherglassaun Lough and Hawkhill Turlough. The phase shift between the peak or trough of the tidal cycle and the resulting response in the turlough should give some idea of hydraulic resistance to flow between the turlough and the sea (*i.e.* small phase shift implies high connectivity or large conduit system, while a large phase shift implies moderate or low connectivity).

Pulling all the turlough water levels together to a standard datum would have been very difficult without the use of Global Positioning System surveying techniques. As described earlier, understanding the potential for flow (or driving head) in any groundwater system is very important. While this is relatively easy to survey on small sites, when looking at a regional system that covers tens of square kilometres using available GPS systems should be considered.

Since 1999, Paul and I have transferred Temporary Benchmarks (TBMs) around the Gort area to set control points (known X, Y and Z locations) at the turloughs we have been monitoring. We have generally used a real time differential GPS system to complete the regional surveying. This has allowed us to plot recorded water levels relative to Malin Head datum. We were lucky enough to be able to hook into the control system for the Gas Pipeline to the West project.

All our control points are linked into at least two Gas Pipeline control points. Once we established control at each individual turlough, we began to survey ground levels, sinkhole and spring levels and other important features in each turlough basin (to date we have completed detailed topographical mapping of Lough Coy, Caherglassaun Lough, Skealoghan turlough, Knockaunroe turlough, Caraunavoodaun Lough, Termon Lough. We have also surveyed parts of Lough Coole and Blackrock turlough). Once the control point (TBM) is in place at a turlough, I have managed to complete site surveys over one or two days depending on the size and complexity of the turlough. Completing the survey myself allowed me the freedom to survey and walk all the dry turloughs. This allowed me to gain a more detailed understanding of locations of springs and sinkholes and their relative elevations.

Variations in Water Level in Caherglassaun Lough Between 04/05/2004 and 15/06/2004 **Figure 12**

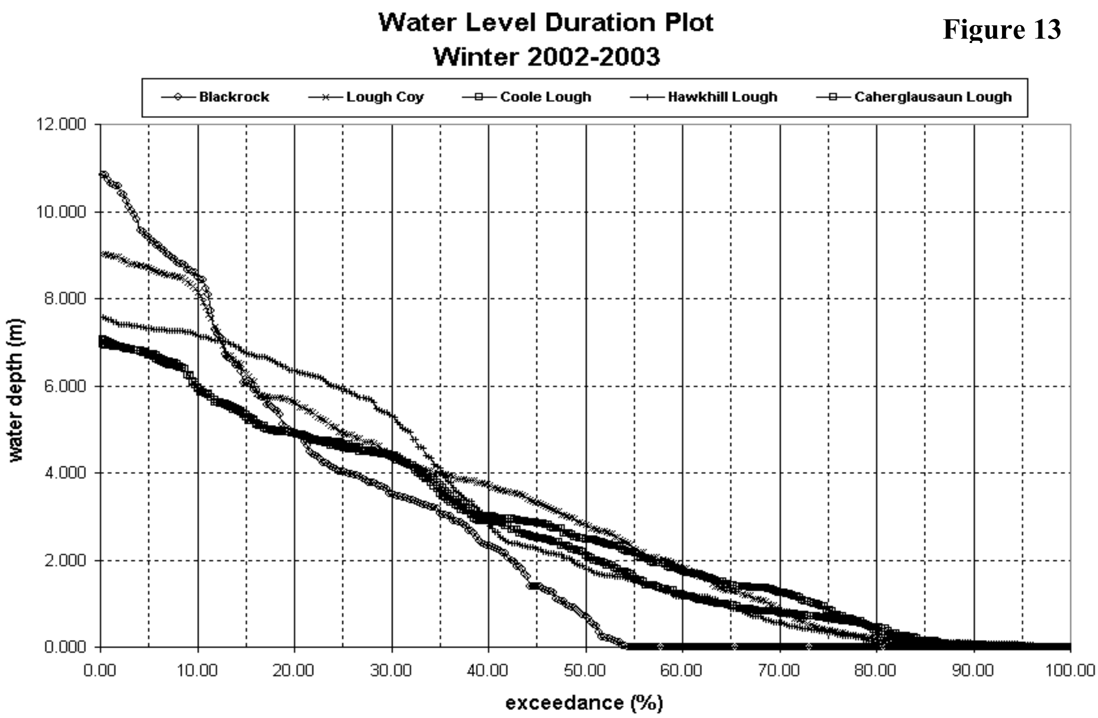


We have used the survey data in conjunction with the water level data outlined above to derive some important hydrological characteristics of turloughs, such as recession constants, duration curves (see Figure 13) and depth-volume relationships. Combining these data with trophic status information has allowed us to attempt to link measures of turlough hydrology to their ecological classification. For example deeper-flooding, conduit-flow-fed turloughs tend to have steep recession constants and are generally eutrophic, while epikarst-fed turloughs have flatter recession constants and are generally oligotrophic or mesotrophic.

In addition to this, we have found definite links between species and community locations at the edges of turlough basins to the depth and duration of inundation (more of this information will be contained in a soon to be published EPA report which Suzanne Tynan (TCD and Jennings O'Donavon Consulting Engineers), Paul and I worked on over the last year or so).

Without the use of GPS surveying and modern pressure transducers the data required to advance our current understanding of turlough eco-hydrology would have taken significantly more time and money to collect. Instead, it has been collected on a part-time basis over the last 5 years with limited manpower and small initial capital outlay. During the coming years, Paul and I intend to expand the current monitoring network and use all-in-one depth/conductivity/temperature probes to monitor some of the more oligotrophic turloughs closer to the Burren.

Figure 13



5.0 CONCLUSIONS

Today there are many useful tools available to hydrogeologists to gather water level data. The development of electronic water level transducers, GPS surveying equipment and GIS software makes gathering and presentation of data easier, cheaper and more reliable than it was 25 years ago.

While our basic understanding of the fundamentals of hydrogeology has not changed, using new equipment should not mean that we forget what we are trying to achieve. New equipment can be used in many different ways, and possibly in ways the manufacturers never envisaged. It is up to the user to determine which piece of kit is most useful depending on the conditions or monitoring requirements at the proposed monitoring site.

We have provided some examples of how we have used different pieces of kit to monitor water levels and chemistry in varying circumstances, and how data gathered in this way have helped us to provide better interpretations of the groundwater environment.

LAPPS QUAY DEVELOPMENT, CORK. DEWATERING AND INSTRUMENTATION – A CASE STUDY

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Toby Roberts, Managing Director, WJ Groundwater Ltd, UK

ABSTRACT

In order to allow the construction of a double level basement in high permeability gravels, adjacent to the River Lee in Cork, a deep well dewatering system was installed and maintained throughout the construction period. Side support was by sheet piles that did not provide a cut-off into the underlying clay. Dewatering wells were installed internally around the perimeter of the excavation. Abstraction flows of up to 280 l/s were required to maintain a dry excavation. Instrumentation and a monitoring system were put in place to measure water levels, within the excavation and externally, abstraction flows and settlement. Data were presented to all relevant parties via the worldwide web.

1.0 INTRODUCTION

The Lapps Quay Development in Cork, Ireland, consists of two buildings one an office/retail development the other a hotel. The two buildings have a combined double level basement car park, approximately 115 metres long and between 40 and 60 metres wide. Prior to construction ground level at the site was at approximately 3 mOD (Malin) and the excavation depth was some 7.5 metres to –4.5 mOD. Side support was by sheet piles on three sides, which formed the permanent basement walls, and along the River Lee a temporary double wall cofferdam was constructed to allow the quay wall to be removed and replaced. The sheet piles were 17 m long and were driven to a depth of -14 mOD.

The thickness of the gravel stratum was not proved across the site and as a result it was considered impractical to provide a vertical cut-off, and a horizontal cut-off was prohibitively costly. In order to allow construction of the basement in dry conditions a dewatering system was installed to lower the groundwater levels within the excavation to below formation level. The system consisted of twenty five deep wells installed internally around the perimeter of the dig. To monitor the performance of the dewatering system, instrumentation was installed to record the water levels both external to the sheet piles and within the excavation. The abstraction flow was also monitored. A plan of the basement area showing the well and instrument locations is shown in Figure 1. Basement construction began in May 2003, and the dewatering was turned off in October 2004, once sufficient super structure was complete to resist floatation forces.

Due to the dewatering works, and the subsequent lowering of groundwater levels within the vicinity of the site there was some concern regarding the settlement risk to adjacent structures. Regular surveying of these structures was carried out to monitor their movement. A trial was also carried out to prove that recharging the abstracted groundwater to external wells could be achieved to reduce the external drawdown should the surveying show that settlement was occurring.

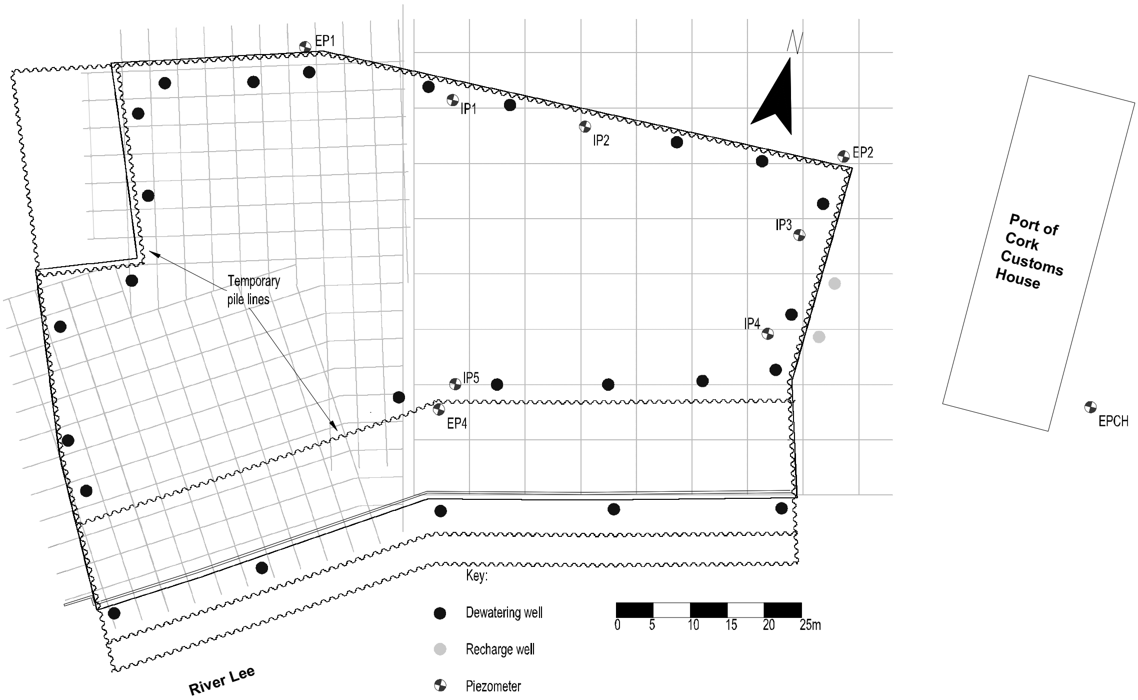

Figure 1: Basement plan showing dewatering well and instrument locations

2.0 GROUND CONDITIONS

Site investigation boreholes indicated that ground conditions at the site comprised made ground overlying alluvium, overlying fluvio-glacial gravels. Below the gravels some of the site investigation boreholes proved the existence of clay, however not all the boreholes went to sufficient depth to show if this was consistent across the whole site. Typical strata depths are given in Table 1.

Table 1: Typical ground conditions

Strata	Thickness	Level of top of strata
Made Ground	2 m	+3 mOD
Alluvium	3 m	1 mOD
Fluvio-glacial gravels	13 m	-2 mOD
Clay (East half of site only)	Not proven	-15 mOD

The alluvium, described as soft grey sandy, slightly gravely silt, is not present in the boreholes drilled along the river front. This was presumably removed during construction of the river wall. The gravels are described as sandy, fine to coarse gravel with occasional cobbles, and are water bearing with a standing groundwater level influenced by tidal fluctuations in the River Lee. During construction the water levels fluctuated from 2 to 4.5 m depth (1 to –1.5 mOD). The gravels are of high permeability; analysis of the particle size distribution, using Hazen's formula, suggested a permeability of the order of 10^{-2} m/s. A pumping test was carried out as part of the site investigation works in February 2003. The test was carried out using a pumped well and an array of piezometers, but analysis proved difficult because of the significant tidal influence on groundwater levels and the absence of any background groundwater level monitoring data prior to pumping or recovery data following pump switch-off. A simplistic analysis suggested the permeability of the gravel was at least of the order of 10^{-3} m/s. Data from other pumping tests in the same formation in Cork indicated permeabilities up to 3.6 x 10^{-3} m/s for the gravels and this value was adopted for design purposes.

3.0 DESIGN

As it was not proposed to drive the sheet piles into the underlying clay, the seepage flow to the basement was dependent on, the permeability of the gravels at and below the toe of the sheet piles, and the distance of influence of the dewatering system. As part of the design work a parametric study using 2D finite element analysis was undertaken using the software package SEEP/W, produced by Geo Slope. The mesh used is shown in Figure 2. The mesh was 230 m long and 30 m deep. No flow boundaries were placed along the base of the model and at the centre line of the excavation. The radius of influence and the gap between the toe of the sheet pile and the top of the clay were varied. The soil permeabilities used in the model are given in Table 2.

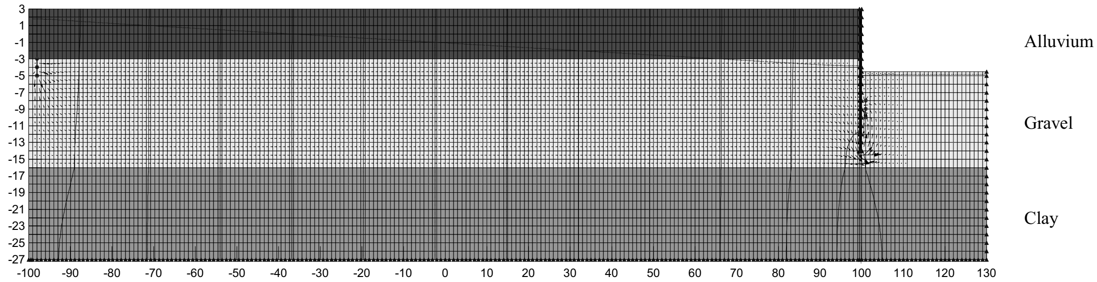

Figure 2: 2D finite element mesh

Table 2: Soil permeabilities used in model

Strata	Permeability (m/s)
Alluvium	1×10^{-6}
Gravel	3.6×10^{-3}
Clay	1×10^{-7}

For a distance of influence of 200 m total inflows to the excavation were estimated in the range 390 to 505 l/s for a toe gap from the piles to the clay of 1 to 4 m respectively. Note that although the River Lee is adjacent to the site it was considered that it would not be in direct hydraulic continuity with the gravels due to the build up of silt and clay on the river bed.

The design was also checked using the estimation of steady state flow rate from CIRIA (2000) using the equation

$$Q = \frac{kDx(H - h_w)}{L}$$

Where, Q is the abstraction flow
k is the permeability (taken as 3.6 x 10^{-3} m/s)
D is the aquifer depth (13 m assumed)
x is the perimeter length (328 m)
H-h_w is the drawdown required (6.5 m)
L is the distance of influence (taken as 200 m).

This analysis, which effectively ignores the presence of the sheet piles, indicated a required abstraction flow of 500 l/s. On this basis the design flow of the dewatering scheme was taken as 500 l/s but it was recognised that this could vary appreciably in practice due to the uncertainties in estimating the permeability of the gravel stratum.

4.0 DEWATERING SYSTEM DETAILS

4.1 DEWATERING SYSTEM

The dewatering system consisted of twenty five deep wells installed internally around the perimeter of the excavation. The wells were located approximately 2 to 3 m from the face of the sheet piles to fit in with other construction works and the permanent structure that was to be built around the wells. The wells were installed to the following specification.

No. of wells	25
Depth	15 m (3 to –12 mOD)
Bore size	300 mm
Liner size	205 mm
Screen length	7.5 m
Pump size	20 l/s

The wells were developed using airlift and surging techniques until the development water was largely free of fines. This typically occurred after 1 or 2 hours of development. The wells were pumped with electric submersible borehole pumps, which were installed to close to the base of the well. Abstracted water was piped from the well using 150 mm header main and discharged to the adjacent River Lee. The system was powered by duty and standby generators. Switch off tests indicated that recovery times in the event of a system stoppage were swift, several metres in a few hours. As a result the electrical control system included fully automatic switch over to standby power and restarting of the pumps in the event of a duty supply failure.

Most of the wells were located within the footprint of the basement. This meant that the base slab was cast around them using a puddle flange sleeve to allow the wells to be capped and sealed on completion.

4.2 INSTRUMENTATION

In order to monitor the performance of the dewatering system instrumentation was installed to measure water levels and abstraction flows. A total of eight standpipe piezometers were installed, five internally to check drawdown was being achieved, and three externally to measure the affects of the system outside the pile line. An additional piezometer was also installed behind the adjacent Port of Cork Customs House building (EPCH). Standpipes comprised standard 50 mm diameter liners with 3 m long screens installed to 10 m depth. Water level monitoring was also carried out in the River Lee. Water level monitoring was carried out using vibrating wire pressure transducers installed in each piezometer and the river and connected to a multi-channel datalogger located in the electrical control cabin. The logger was programmed to record readings at 15 minute intervals throughout the works.

Abstraction flows were measured by 150 mm electromagnetic flowmeters installed in the discharge lines. These were also connected to the datalogger to allow automated monitoring. The datalogger also acted as an alarm system, notifying the site staff immediately, via a GSM modem, if a pump failed or water levels rose above predefined limits.

4.3 MONITORING

Data were collected from the logger on a daily basis via the GSM modem. To allow rapid presentation of the data and easy access for all the parties involved in the project, in both the UK and Ireland, the data was presented via the web. This was an automated process allowing the data to be available to the relevant people within minutes of it being collected and from anywhere with internet access. An example of the data on the website is given in Figure 3.

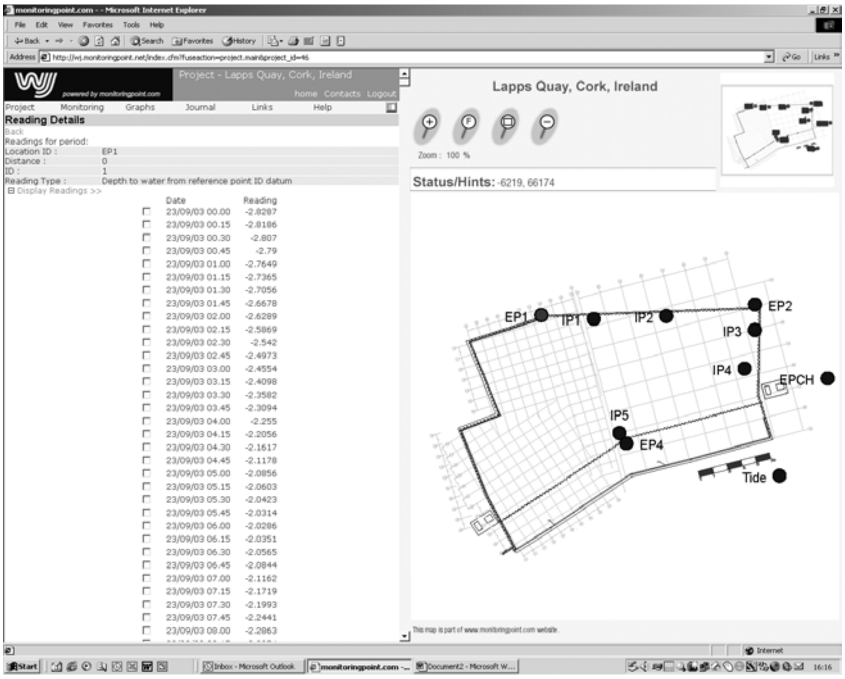

Figure 3: Example of data on website

The openness with which the data was available led to a high level of confidence, within all parties, that the system was achieving its aim.

5.0 SITE DATA

5.1 WATER LEVELS & ABSTRACTION FLOWS

The water levels during the early stages of pumping are shown in Figure 4. This shows that the average river level and background standing water levels, prior to pumping, are around 0 mOD, and that the tidal response ranges between approximately +2 and –2.3 mOD.

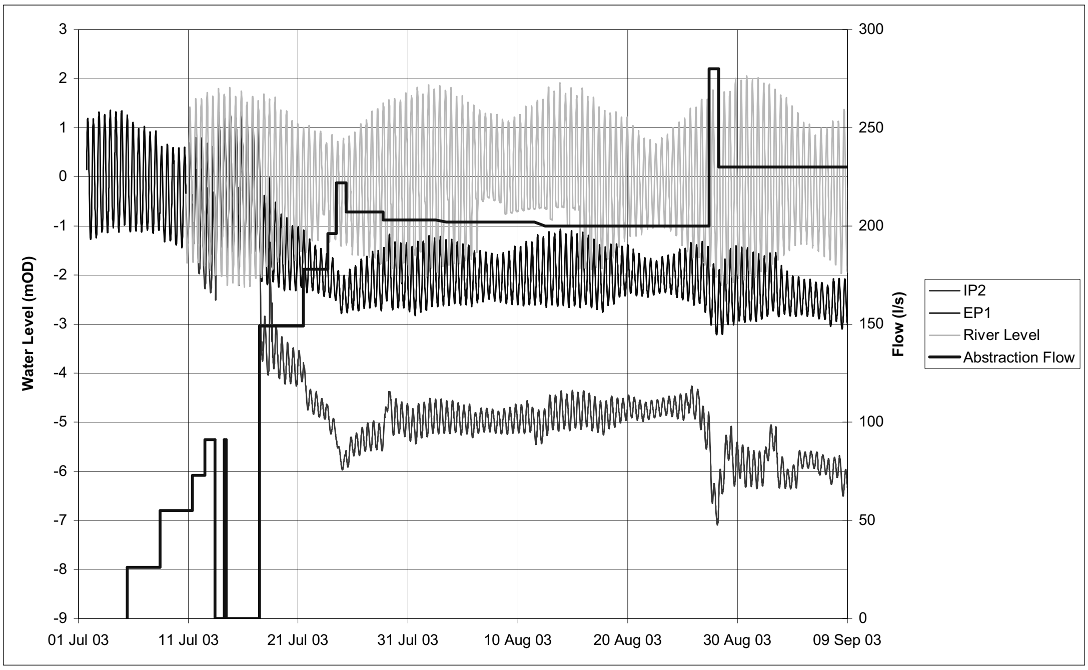

Figure 4: Early stage water level and abstraction flow data

The pump switch-on was a phased process which began on 5 July 2003 with flows stepping up as wells are activated. The peak flows measured were of the order of 280 l/s. Figure 4 also shows the water levels from a typical external (EP1) and internal piezometer (IP2). Drawdown to below the target level of –5 mOD within the excavation is achieved during August 2003. The external piezometer is also drawn down during the pumping, the average water level being about –2.5 mOD by September. Therefore the difference between the average river level and the average water levels external to the excavation is approximately 2.5 metres. However, the difference between the river lows and the low levels recorded in the piezometer are only of the order of 1.5 metres.

The relationship between drawdown and flow is shown in Figure 5, this indicates an abstraction flow of approximately 34 l/s per metre of drawdown. Back analysis of the dewatering system was undertaken using the SEEP/W finite element model. The gravel layer was subdivided into an upper layer above –12 mOD, which was taken to have a permeability of 5 x 10^{-3} m/s and a lower layer below –12 mOD. The permeability of the lower layer was varied until a reasonable fit was obtained with the abstraction flow, internal and external drawdowns. The best fit was obtained with a permeability of the lower gravel of 6 x 10^{-4} m/s.

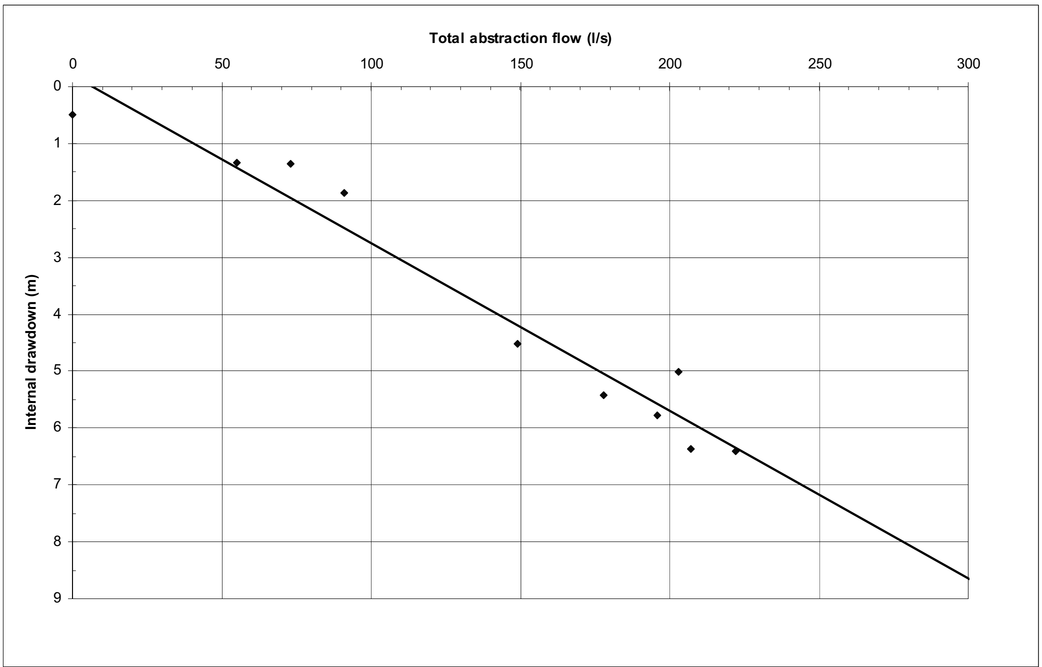

Figure 5: Drawdown flow relationship at high tide

5.2 RECHARGE TRIAL

Due to the concerns regarding external drawdown, and possible settlement, a recharge trial was carried out in two wells drilled externally between the sheet piles and the Port of Cork Customs House building. A portion of the abstracted water was fed to the wells via an electromagnetic flowmeter. The monitoring data from the nearest external piezometer (EP2) and that installed near the Customs House building (EPCH) are shown in Figure 6, as well as the recharge flows. It is apparent from the data that there was a response of the external water levels due to the recharge, however the magnitude of the rise is difficult to quantify due to the tidal response. Looking at the data more closely on 23 October, when the recharge flow was stepped up to over 20 l/s, and on 13 November, when the recharge was switched off, the change in the peak levels before and after each event is approximately 0.6 m for EP2 and 0.4 m for EPCH. However, it should be noted that these levels are also affected by the tide heights.

At various stages during the trial the recharge wells had to be redeveloped due to a drop in capacity because of clogging. Evidence from site of iron staining would suggest that the clogging of the wells was due to iron related bio-fouling (Powrie et al, 1992). Chemical analysis of the abstracted water indicated dissolved iron concentrations of approximately 1 mg/l which, from experience, is sufficiently high to have been the primary cause of the gradual deterioration in recharge well capacity. The recharge flows between 2 November and 13 November gives a good indication of how the capacity of the recharge wells fell over time if left to run without any redevelopment work. This would indicate a fairly rapid decrease in capacity of the wells. If recharge was required for extended periods then regular well cleaning and redevelopment work would be necessary to maintain the flow.

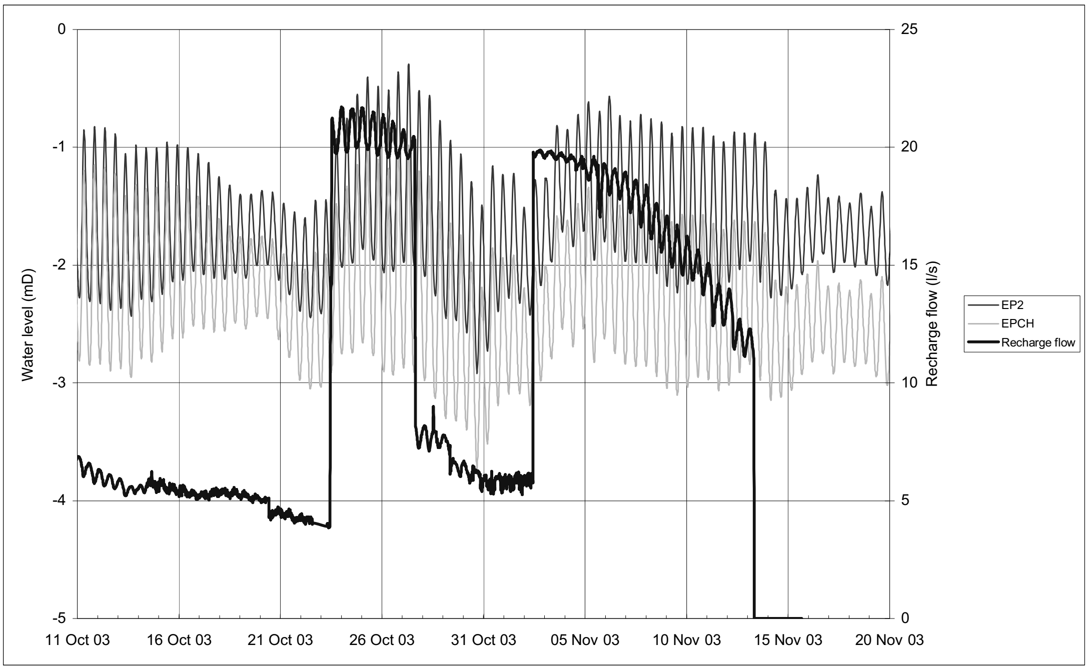

Figure 6: External water levels and recharge flow

5.3 SETTLEMENT

There are three factors, which control the amount of settlement induced by external drawdowns as follows,

- The soil stiffness,
- The thickness of soil affected by the ground water lowering,
- The amount of groundwater lowering.

The Made Ground was generally present above the standing groundwater level and so would not be influenced by the drawdown. Information on the stiffness of the gravels was limited comprising standard penetration testing in the site investigation boreholes. It was considered that the gravels were sufficiently dense that any settlement of the gravels would be nominal (less than say 3 mm). The primary concern was the alluvium, which was soft and potentially susceptible to consolidation, even at the relatively small loads induced by groundwater lowering. Data from oedometer testing of two alluvium samples taken from the borehole EPCH indicated a soil stiffness, E’ = 2.5 MPa. CIRIA (2000) defines the ‘basic settlement’ as the compression of a soil layer 1 m thick from an increase in vertical stress resulting from a drawdown of 1 m. Basic settlements are given by 10/E’ or 4 mm for the alluvium. The alluvium was 3 m thick typically and susceptible to full under-drainage, giving an average drawdown of 1.5 m, and estimated potential settlement of 18 mm. It could be argued that only the alluvium below 0 mOD is subject to the drawdown, which would reduce the settlement estimate to 8 mm.

The extent to which a structure would be affected by any consolidation would depend on the structures foundation bearing level. Of particular concern in this case was the Port of Cork Building, which was located within 20 m of the sheetpiles. This is a historic building with stone façade, the foundation details of which are unknown. The building was in good condition implying that it was probably founded on the gravels but this could not be confirmed. The settlement of the alluvium would be time dependent. Analysis based on the oedometer tests suggested that ultimate settlements would take several months to develop. However a significant proportion of the ultimate settlement should have been evident within a few weeks of commencing pumping. Movement was monitored closely by regular levelling of targets on the adjacent structures. In the event the monitoring did not detect any movement beyond the accuracy of the instrument. It was therefore deemed not necessary to implement a recharge system.

6.0 CONCLUSIONS

A deep well dewatering system was successfully installed and maintained to allow the construction of a double basement in high permeability gravels. Abstraction flows of up to 280 l/s were required to maintain the required drawdown of approximately 6 metres.

Instrumentation was installed to prove the performance of the dewatering system and monitor external drawdown. Data were presented on the worldwide web for ease of access for staff on site, and in offices in both Ireland and the UK.

A recharge trial was carried out to ensure that abstracted water could be recharged to maintain water levels and protect adjacent structures from possible settlements. Recharge was considered a viable option although the presence of dissolved iron in the groundwater would have lead to a maintenance requirement to control deterioration in the recharge system capacity.

Settlement monitoring of adjacent structures showed that no detectable movement was occurring, therefore recharge of the abstracted water was not required. This was probably because the structures of concern were founded on the gravel stratum which was dense, and therefore not susceptible to significant settlement induced by groundwater lowering. It may also have been because the alluvium soils were stiffer than suggested from the site investigation information.

7.0 ACKNOWLEDGEMENTS

The authors would like to thank P J Hegarty & Sons and Walsh Goodfellow Consulting Structural and Civil Engineers for their kind permission to publish the paper.

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WATER TRACING IN KARSTIC AQUIFERS: CURRENT METHODS

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ABSTRACT

Water tracing is a well-established technique for investigating groundwater conditions particularly in fissure and/or conduit dominated groundwater flow systems. Karst aquifers are thus particularly well suited to tracer investigations. An acceptable method of water tracing must fulfill certain criteria, some mandatory (e.g. harmlessness to humans and to the environment), others desirable but not essential. At present two tracer methods are the most widely used and most highly developed. Fluorescent dyes detected by fluorometry are a reliable, relatively simple and inexpensive method of tracing. Bacteriophage tracing is more expensive and requires specific technical expertise for its use but is comparable to dye tracers in sensitivity and reliability. Both types of tracer allow multi-tracing and the acquisition of subsidiary hydrological data from the tracing experiments. Water tracing is a relatively underdeveloped technique in Ireland despite its obvious relevance to the mainly karstified aquifers Desirable refinements in water tracing methods include the development of tracers that are functional in non-karstic aquifers and tracers which are suited to trace biologically contaminated waters.

1.0 INTRODUCTION

Although water tracing has been used in groundwater investigations for more than a century, primarily to trace sinking streams in karst, it has only been in more recent times that the techniques have been refined into quantitative methods capable of yielding an array of data concerning groundwater conditions. However it is still the case that water tracing is most widely used and most usefully deployed in karstified limestones. In theory Darcy's Law allows for the prediction of groundwater flow directions and rates but in practice it has little or no validity in groundwater systems dominated by fissure or conduit flows is almost always the case in limestone aquifers. To some extent water tracing experiments can provide such data on groundwater flow, particularly in conditions where point recharge and spring discharge operate. However, the use of tracers in matrix flow and subsoil environments remains ill-researched and of limited value

2.0 CRITERIA FOR A USEFUL TRACING METHOD

All tracing methods must use non-toxic and inoffensive tracers; must be detectable at low concentrations; and must yield clear and unambiguous results. It is also desirable that the method should be relatively cheap and foolproof, yield subsidiary qualitative or quantitative data and permit tracing from several locations within an aquifer simultaneously (multi-tracing).

The tracer itself (matter or energy carried by the water and which distinctively labels a batch of groundwater) should be conservative within the aquifer, should not be present naturally in significant quantities and should not be affected by the physics or chemistry of the groundwater.

The method used for detection of the tracer in water samples taken from locations in the groundwater body must effectively and unambiguously isolate and identify the tracer in very low concentrations. Ideally, automatic sampling for the tracer should be possible.

3.0 TYPES OF TRACER

Tracers fall into five main categories: fluorescent dyes, biological materials, particulate tracers, chemicals and stable isotopes/radio-isotopes. In practical terms the vast majority of water tracing experiments undertaken at present use either dyes or biological agents and it is only these two tracer types that are considered in this paper. Fluorescent dyestuffs, including the use of optical brighteners probably account for in excess of 90% of all tracings.

3.1 FLUORESCENT DYES

Although fluorescent dyes are visible at low concentrations in water, their real value in water tracing is that they can be detected at concentrations up to 6 orders of magnitude lower then the threshold of visibility by detecting the light emitted by the fluorescent dye molecule. This detection, is usually undertaken using a fluorometer which can be used in the field as well as the laboratory and can be adapted to give continuous 'flow through' readings of fluorescence. In addition by measuring only that radiation emitted at the particular wavelength for a dye it is possible, in theory, to distinguish numerous dyes with different emission wavelengths and thus enable multi-tracing. In practice only two dyes are widely used, Sodium Fluorescein a green dye normally available in powder form and Rhodamine WT or Sulpha-rhodamine, a red dye normally sold as a 20% aqueous solution. This is because it is difficult and time consuming in the laboratory to separate dyes having emission wavelengths close to one-another in a water sample, whilst the two dyes mentioned have very separate absorbtion and emission wavelengths of radiation. Samples for analysis are normally in the form of water samples (grab samples) of 50-100ml taken from sites, it is possible to leave detectors of activated coconut charcoal ('bugs' or 'fluorocaptors) in the flow of the water. The charcoal sorbs the dye and the dye can later be elutriated from the detector and analysed using fluorometry.

Dyes are the simplest and most reliable of tracers but problems still arise in their use.

A major problem is to decide on the quantity of dye required for a particular tracing experiment. Dye concentrations at sampling points or at other locations where the groundwater is used or visible need to be below the visible threshold of c.1ppm. Dilutions also need to be within the limits of fluorometric detection (c. 1ppt). A variety of formulae have been suggested to estimate the quantity required. The formula empirically derived by S. Worthington has been used with reasonable success in Ireland:

$$\mathbf{M = 17(L . Q . C) . 0.93}$$

where M = mass of dye required in gram, L = length of flowpath, Q = discharge at sampling point, C = dye concentration at the sampling point High levels of suspended matter in the waters may require considerable greater dye inputs. Organic (peaty) water, common in upland Ireland discolour most dyestuffs very effectively. The low pH of such waters also lessen the emission of radiation from the dye though this can be compensated for in the laboratory subsequently.

Background levels of fluorescence at wavelengths close to that of the dyes (particularly Fluorescein) are not unusual and are thought to be largely biological in origin. Such background emission must be checked for and if present allowed for, during the test.

The use of charcoal detectors also has difficulties. Rhodamine is much less easily sorbed and eluted that Fluorescein; background fluorescence is enhanced disproportionately; quantitative analysis of the trace is difficult and ambiguous results are relatively frequent.

3.2 OPTICAL BRIGHTENERS

Optical brighteners are fluorescent substances with an affinity for fabrics, especially cotton. They are difficult to detect with a fluorometer and detectable only at much lower concentrations than fluorescent dyes However, these problems are compensated for to some extent by the ease of detection using cotton suspended in the flow water at a sampling point. The optical brightener is adsorbed on to the cotton and retained. The presence of the optical brightener can be checked for later by exposing the detector to ultra-violet light. All major chemical companies manufacture optical brighteners and they are available as in liquid or powder forms. Tinopal LPW or 4Bm and Leucophor are commonly used optical brighteners. Optical brighteners require the minimum of equipment and expertise for their use in tracing and are well suited to single traces designed to confirm a hydrological link.

Problems with their use include:

1. The presence of optical brighteners in the aquifer, derived from industrial or domestic (detergent) sources and serving to obscure the outcome of a trace or, at worst, give false positive results. It is test the sampling sites for the existence of background concentrations of optical brighteners in the waters prior to any tracing.
2. Cotton detectors sometimes discolour if left in natural waters for any length of time often making the identification of positive detectors ambiguous or impossible.
3. Large volumes of tracer are often requires (several kilograms)and estimating the amount required for a particular trace is an inexact science.

3.3 BACTERIOPHAGE

Phage are highly specific viral forms with each type having a host bacterium. They function as a particulate tracer, moving as suspended load with the groundwater flow. However, unlike other particulate tracers such as lycopodium spores or polystyrene latex spheres, their detection is by biological means by introducing a sample of water to a culture of the host bacterium and observing the destruction of the bacteria if the phage is present. their detection Their density (1 micron) and diameter (011micron) means that they can move with the natural flow of water in all but the most fine-grained of aquifers. Several (>9) types of phage may be used simultaneously making large scale multi-tracing an option.

The disadvantages of using phage as tracers includes the relative expense of the method, the microbiological expertise required for cultivating phage and analyzing for their presence and uncertainty as to the effects of introducing alien phage into groundwater systems.

4.0 WATER TRACING IN IRELAND

The main aquifer in Ireland is the Carboniferous limestone in which karstification is ubiquitous and in some areas extreme. Despite this, water tracing as an investigative technique has not been employed frequently or systematically. Much of the tracing has been 'academic' in character – for example on the Burren plateau in Co. Clare. However, recently water tracing has been undertaken in conjunction with several Groundwater Protection Schemes at county level and these have contributed considerably to understanding of the functioning of these aquifers. More often tracing has been confined to basic traces designed to determine specific underground links. Thus, in comparison with the frequently utilized conventional techniques of surface geophysical methods and borehole pumping tests, water tracing is an under-utilised tool. Given that groundwater contamination in Ireland is often of agricultural origin and of microbiological character, the further use of and development of, bacteriophage tracing would seem appropriate.

5.0 CONCLUSIONS

Recommendations for the execution of successful water tracing experiments would include:

1. The use of fluorescent dyes with fluorometric detection or the use of bacteriophage.
2. If charcoal detectors are used or optical brightener cotton detectors be alert to possible ambiguous results
3. Plan the test carefully especially with regard to the type and quantity of tracer used, the selection of sampling sites and the duration and frequency of sampling.
4. Develop a strict protocol for both the field and the laboratory aspects of the tracing experiment.

Although water tracing is now a well developed techniques, problems remain to be resolved. These include the difficulty in assessing the optimal amount of tracer required for a particular tracing, being certain that a negative result from a sampling site really indicates that the water does not flow to that site and tracing groundwater movement in non-karstified aquifers and in particular in aquifers with dominantly inter-granular flow.

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A NEW APPROACH FOR ANALYSING TEST PUMPING DATA IN HETEROGENEOUS AQUIFERS – IMPLICATIONS FOR QUARRYING

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Page 1 of 4

Session IV

New Tools and Practical Examples II

Is this Diesel mine…? ADVANCES IN FORENSIC IDENTIFICATION USING SOURCE SPECIFIC MARKERS OF PETROLEUM RELEASES INTO THE ENVIRONMENT

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ABSTRACT

Recent developments in forensic hydrocarbon fingerprint analysis have enabled specific markers found in diesel to be characterised and identified. Fingerprinting and data interpretation techniques include the recognition of distribution patterns of hydrocarbons which include the alkylated naphthalene, phenanthrene, dibenzothiophene, fluorene, chrysene and phenol isomers; analysis of "source-specific marker" compounds, individual saturated hydrocarbons, including n-alkanes (n-C_5 through n-C_{40}), alkylcyclohexane homologues series, and the recalcitrant isoprenoids: pristane and phytane; the determination of diagnostic ratios of specific petroleum and non-petroleum constituents; and the application of various statistical and numerical analysis tools[1-5]. A spill sample was analysed to identify the possible source and origin of the petroleum contaminant (diesel). Samples were subjected to analysis by gas chromatography, utilising both flame ionisation and time of flight mass spectral detection techniques (TOF-MS) in comparison to known reference materials. The analysis showed the diesel came from the suspected source. This allowed the regulator to prosecute.

1.0 INTRODUCTION

The study follows the forensic investigation into the source identification of home heating fuel accidentally spilled when delivered to a domestic house. It was suspected that the homeowner was adding a petroleum product to the spill area to increase the value of the insurance claim. A sample was taken from the tank and compared to soil samples taken in the spill area.

2.0 ANALYTICAL APPROACH

Hydrocarbon fuels and derivatives found in the environment are often characterised by gas chromatography/flame ionisation detection (GC/FID). The identification and interpretation of GC fingerprints is largely qualitative and subjective, as it is dependant upon the skill and expertise of the interpreter. It is for this reason that a tiered approach is adopted to give a quantitative and objective interpretation of the analytical data using the following[6]:-

Level 1 – Chemical Fingerprinting by GC-FID
Level 2 – Detailed Analysis by GC-TOF/MS
Level 3 – Statistical Analysis of the Data

Prior to analysis by gas chromatography the soil sample was coned and quartered and an aliquot was submitted for moisture content and a further aliquot was submitted for solvent extraction. This extract was analysed using the tiered approach (Figure 1) [6].

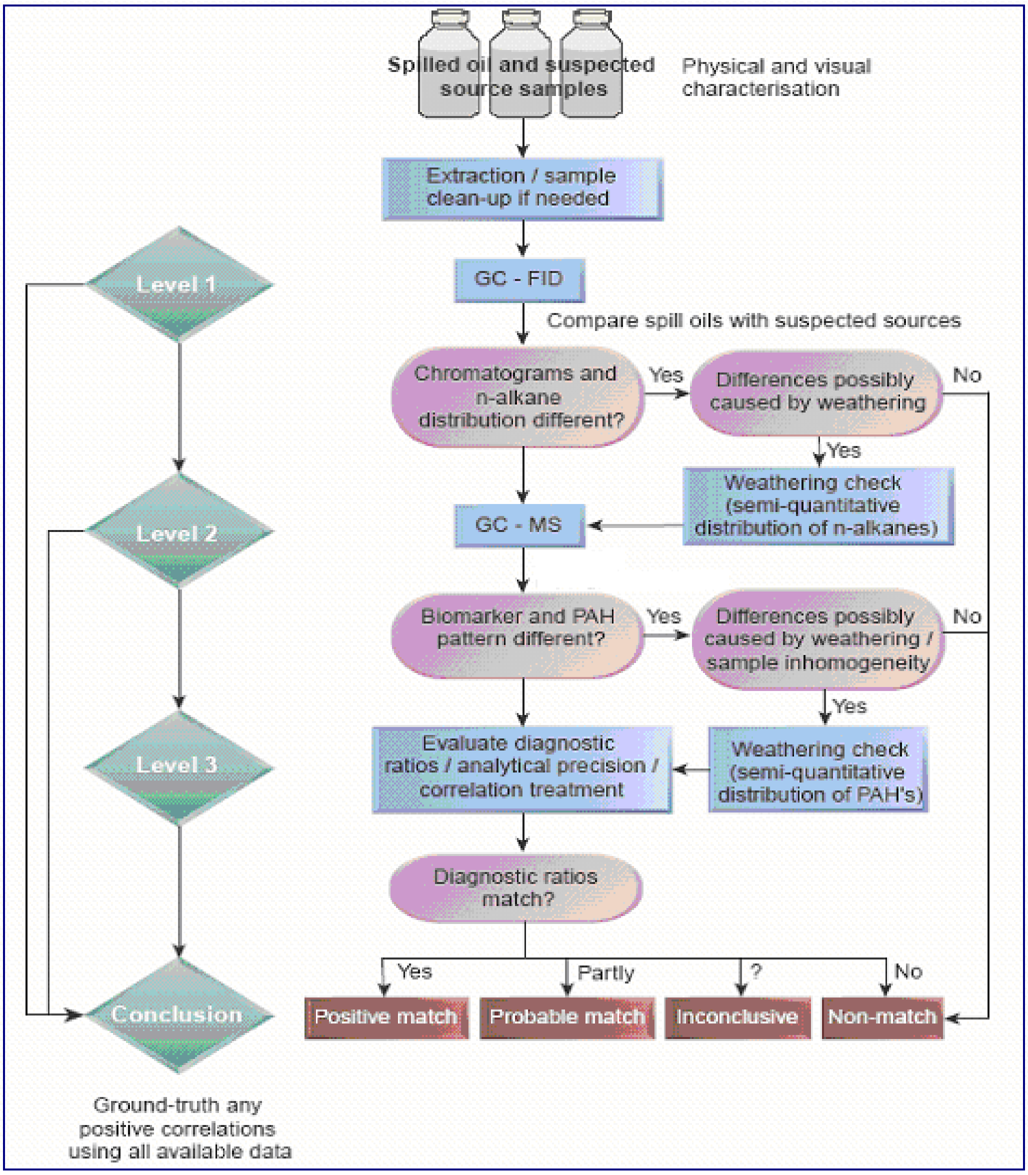

Figure 1 Tiered Three Level Approach[6]

2.1 LEVEL 1 - CHEMICAL FINGERPRINTING BY GC-FID

Identification of the product type in contaminated samples is the single most important stage in any environmental forensic investigation as it frequently forms the foundation on which many of the relevant conclusions are derived. Among the analytical methods used to identify a wide range of contaminants are those that focus on specific hydrocarbon classes, such as alkanes and alkylated polycyclic aromatic hydrocarbons (PAHs). This screening Level 1, allows for the general characterisation of the sample for volatile petroleum hydrocarbons (VPH) in the carbon ranges n-C_5 to n-C_9, n-C_{10} *to* n-C_{12} and extractable petroleum hydrocarbons (EPH) in the carbon range n-C_{10} to n-C_{40}. The tank sample was characterised for both VPH and EPH. The EPH characterisation of the contaminated soil sample located around the spill site revealed a fingerprint profile indicating a bimodal unresolved complex mixture (UCM) profile (Figure 3). The observed carbon range n-C_{10} to n-C_{27} is characteristic of kerosene and diesel [7-10].

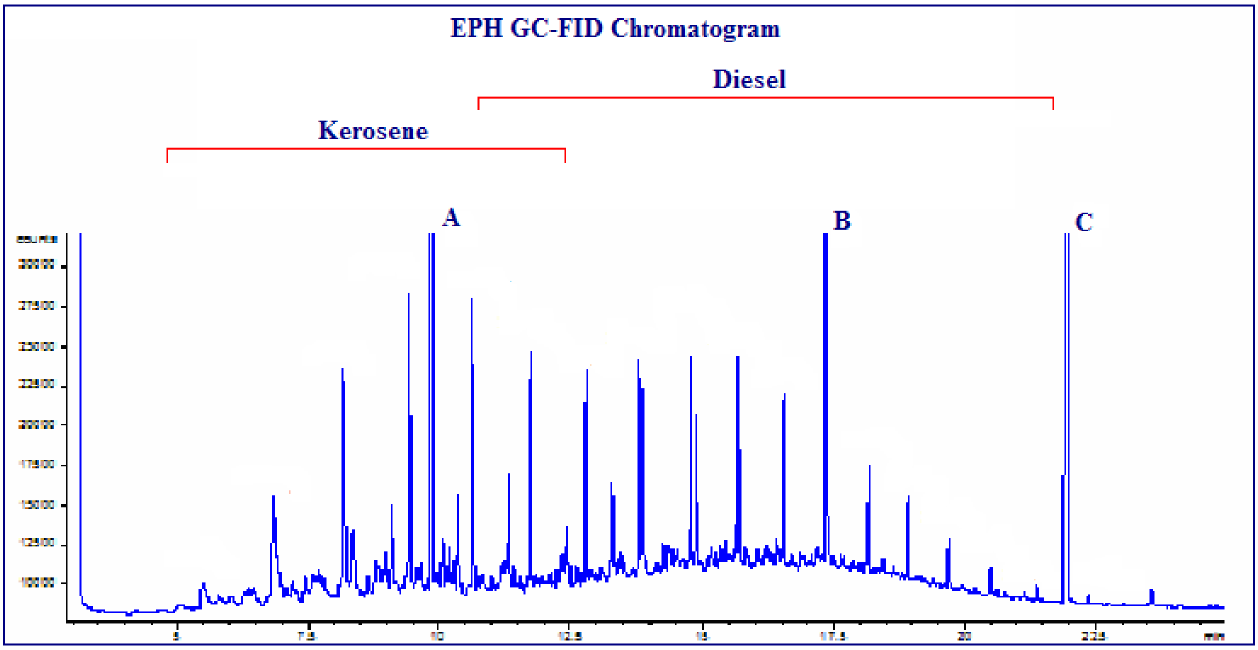

Figure 3 EPH Characterisation – Soil

2.2 LEVEL 2 – DETAILED ANALYSIS BY GC-TOF/MS

The next analytical "level" involves analysing the extracts and candidate source samples by Time of flight GC/MS. This helps determine the content and profile/distribution of a suite of petroleum or source specific alkylated PAH target analytes. The unique power of the time of flight mass spectral investigation involves the use of its deconvolution software combined with retention time locking (RTL) allowing for reduced risks of false positives[11].

Chemical analysis of source-characteristic and environmentally persistent source specific markers generates information to determine the possible source of spilled products, differentiating products, monitoring degradation and weathering under a variety of conditions. In the past decade, these fingerprinting techniques were used to study spilled products has greatly increased, and been playing a prominent role in almost all spill work[4,8,10,12-20]. In general qualitative chemical analysis and visual comparison of chromatograms of a contaminated soil sample by GC/FID or GC/MS determined in **Levels 1** and **Level 2** with suspected candidate source, may sufficiently meet the needs of most forensic investigation. Diagnostic information was obtained by examining the chromatographic data from the tank and soil samples using selected alkyl homologues of the primary PAHs, in addition, sulphur containing compounds such as dibenzothiophene and its alkyl derivatives were used to access the source[4,8,10,12-20]. Table 1 lists the alkylated PAH compounds, the number of benzene rings in each compound and the selected ion monitoring (SIM) mass to charge (m/z) ions used during this investigation[21].

Table 1 Alkylated Polycyclic Aromatic Series[4,8,10,14-22]

Compound	*Ring No*	m/z
Naphthalene Series		
C_0-naphthalene	2	128 *m/z*
C_1-methylnaphthalene	2	142 *m/z*
C_2-dimethylnaphthalene	2	156 *m/z*
C_3-trimethylnaphthalene	2	170 *m/z*
C_4-tetramethylnaphthalene	2	184 *m/z*
Phenanthrene Series		
C_0-phenanthrene	3	178 *m/z*
C_1-methylphenanthrene	3	192 *m/z*
C_2-dimethylphenanthrene	3	206 *m/z*
C_3-trimethylphenanthrene	3	220 *m/z*
C_4-tetramethylphenanthrene	3	234 *m/z*
Dibenzothiophene Series		
C_0-dibenzothiophene	3	184 *m/z*
C_1-methyldibenzothiophene	3	198 *m/z*
C_2-dimethyldibenzothiophene	3	212 *m/z*
C_3-trimethyldibenzothiophene	3	226 *m/z*

However, when the chemical similarity/difference between spilled product and suspected source is not obvious, or a large number of sources are involved, or where the spilled product has undergone a degree of weathering, or significant alteration in its chemical composition, the quantitative approach can be difficult, and therefore the qualitative analysis of degradation-resistant PAH compounds should be performed[4,8,10].

2.2.1 Naphthalene Alkylated Series

Figure 5 depicts the TOF-GC/MS analysis of the tank sample selecting the m/z ions for the naphthalene alkylated series along with the chemical structure of naphthalene and its methyl naphthalene isomers. The individual isomers are targeted and the depletion of these isomers can be used to assess the degree of weathering or biodegradtion[22]. The fragmentogram indicated minimal depletion of the series[10].

Tank Sample **Soil Sample**

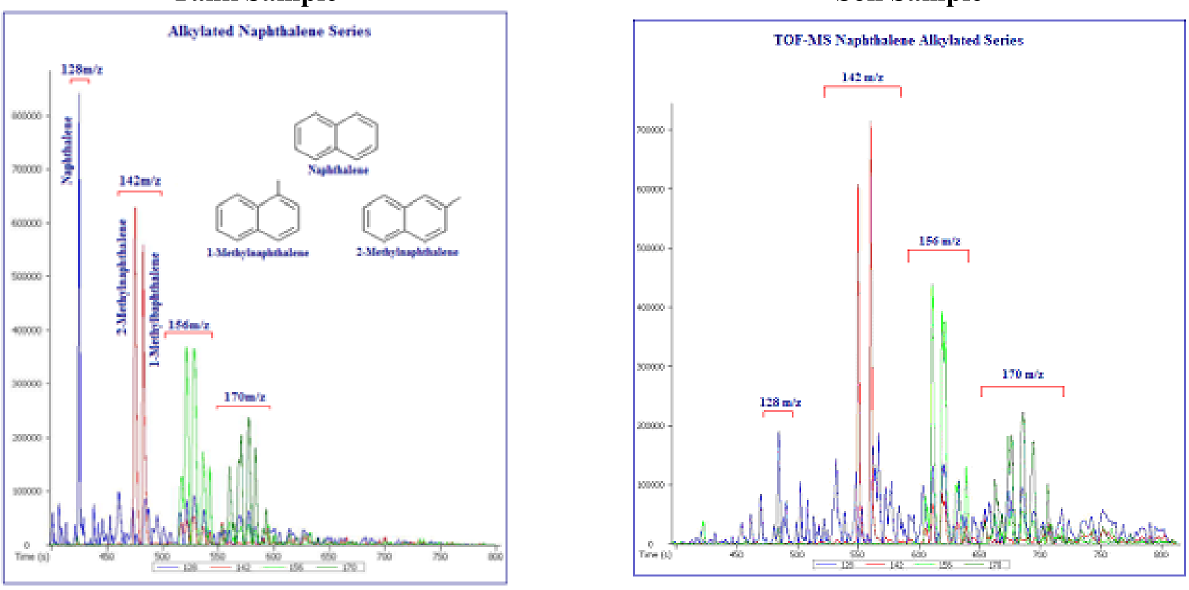

Figure 5 Naphthalene Alkylated Series

2.2.2 Phenanthrene Alkylated Series

A reduction in the ratio of 2-methylnaphthalene compared to the 1-methylnaphthalene isomer in the naphthalene series fragmentogram (Figure 5) indicated some weathering of the parent naphthalene ion. This indicates some alteration following the spill[12-20].

Another alkylated series is phenanthrene and its associated methylphenanthrene and dimethylphenanthrene isomers (Figure 6). The alkylated ions were monitored to target the selected ions for each phenanthrene isomer ($C_{14}H_{10}$). The presence and depletion of these isomers can give information about the degree of weathering, biodegradation or can be used in source correlation studies. The Tank sample (Figure 7) indicated the presence of no phenanthrene alkylated isomers which is characteristic of a kerosene fuel oil[4,8,10,12-20].

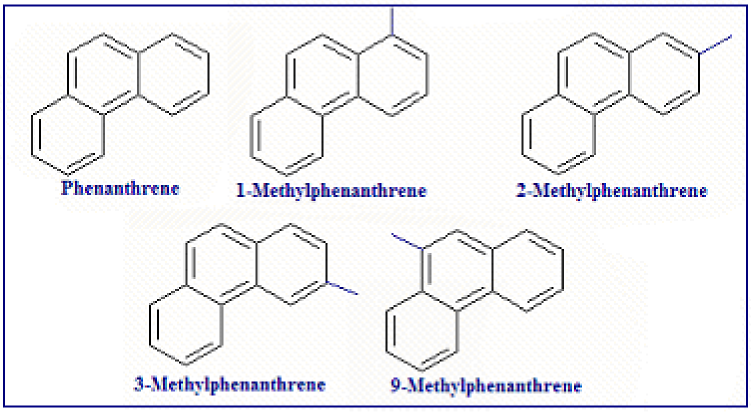

Figure 6 Chemical Structures of Phenanthrene Series

Tank Sample **Soil Sample**

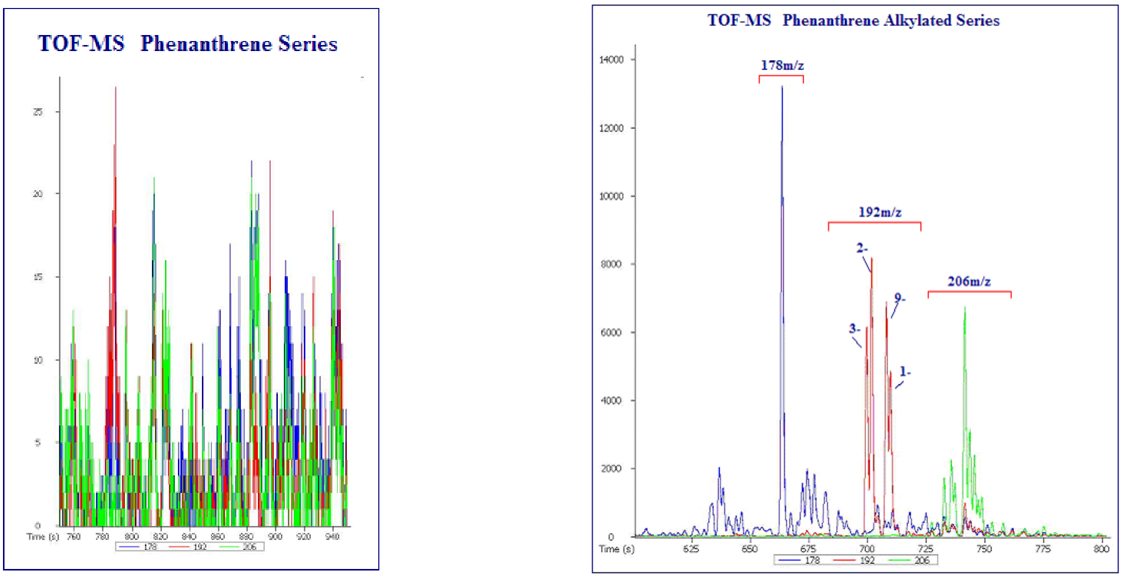

Figure 7 Phenanthrene Alkylated Series

The data obtained from the chromatogram of the soil sample were reviewed for the parent phenanthrene ion and its associated methylphenanthrene and dimethylphenanthrene isomers (Figure 7). The abundance of the series in the soil sample indicated a second source to the contaminated site which confirms the EPH bimodal chromatogram from the Level 1 investigation[4,7,8,10,12-20].

2.2.3 Dibenzothiophene Alkylated Series

A similar approach was used for dibenzothiophene (Figure 8) alkylated series as for naphthalene and phenanthrene isomers[7, 10].

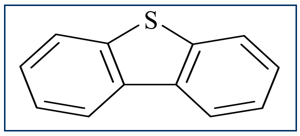

Figure 8 Chemical Structure of Dibenzothiophene

The fragmentogram of the data obtained from the Tank sample indicates an abundance of tetramethylnaphthalene isomers (184m/z). This confirms the abundance of the naphthalene series in kerosene. The same ion is used to select the parent dibenzothiophene compound which is absent from the fragmentogram (Figure 9)[7, 10].

Prior to the year 2000, diesel contained a range of sulphur compounds[7, 10] the introduction of low sulphur diesel resulted in the reduction of the sulphur isomers in diesels. The presence or absence of these isomers can be used to age products as well as being used to correlate source. The abundance of the dibenzothiophene series confirms the findings of the phenanthrene series (Figure 9)

Tank Sample **Soil Sample**

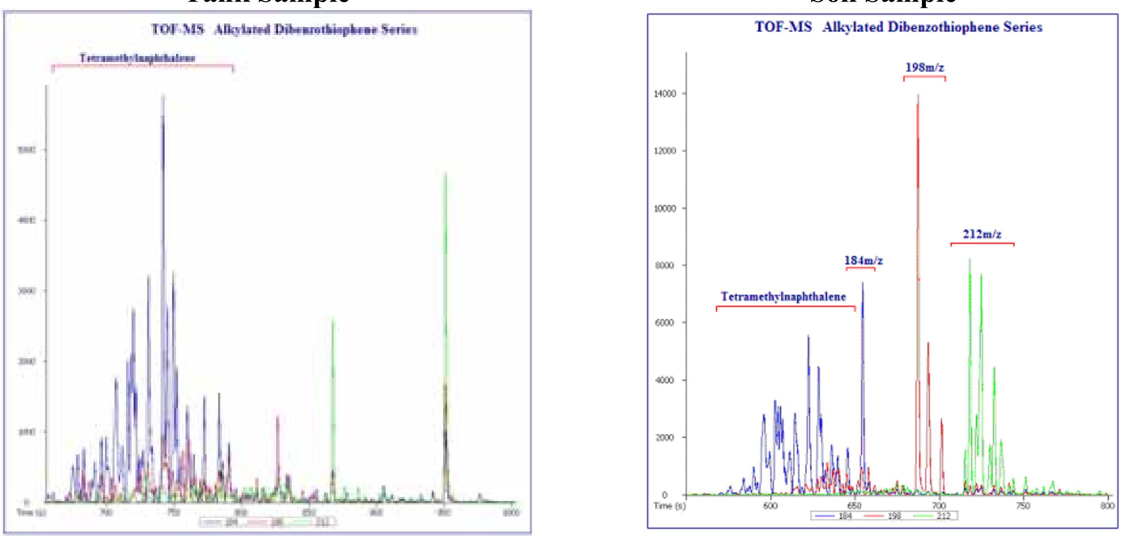

Figure 9 Dibenzothiophene Alkylated Series

2.2.4 Alkylcyclohexane Series

Another group of compounds namely alkylcyclohexanes was also targeted in both samples. These compounds belong to a class of naphthenes or cycloparaffins, the most common molecular structures found in petroleum. These compounds form a homologous series similar to n-alkanes but are more resistant to biodegradation. These homologous series of compounds are present in refined oils such as gasoline, kerosene and gas oil but the profile and distribution patterns are different. For gasoline, the distribution exhibits an asymmetric rapidly decreasing pattern from methylcyclohexane to heptylcyclohexane. Kerosene is characterised by a distribution pattern in the range ethylcyclohexane to decylcyclohexane with a maximum abundance at propylcyclohexane. Gas oil exhibits a much wider range from methylcyclohexane to hexadecylcyclohexane with a maximum at nonylcyclohexane (Figure 10). The profile can be used to determine the type of product present or can be used to assess whether mixtures of products are present and the degree of weathering or biodegradtion[7].

The data obtained from the analysis of the Tank sample clearly demonstrates a distribution of the alkylcyclohexane series for methylcyclohexane to decylcyclohexane with a maximum at propylcyclohexane. The typical distribution for a diesel was observed for the Soil sample[7].

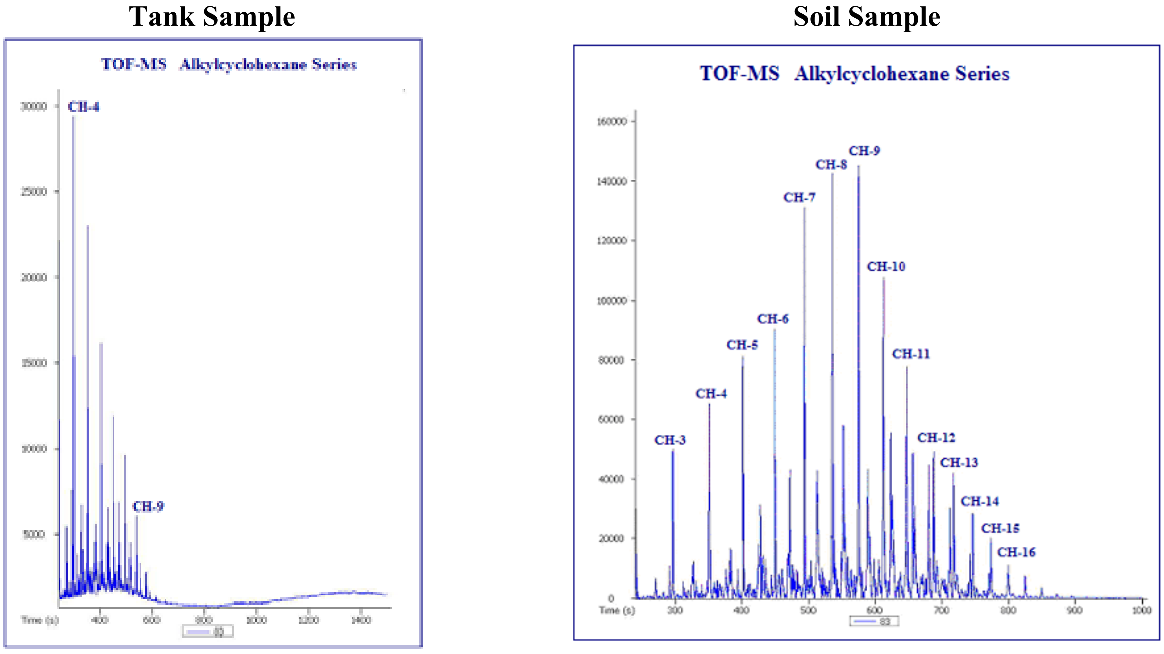

Figure 10 Alkylcyclohexane Series

2.2.5 Pristane and Phytane

The source specific markers in diesel typically used in age analysis are the recalcitrant isoprenoid compounds, of which the two most abundant are pristane and phytane (Figure 11). The degree of change in diesel within the subsurface environment may be measured by comparing ratios of compounds with different physical, chemical or biological properties. The n-alkanes are readily biodegraded and the pristane and phytane are recalcitrant, and therefore ratios of these compounds can be used. The most common ratios are n-C_{17}/pristane, n-C_{18}/phytane and pristane/phytane[4.8.9,10,12-20, 23].

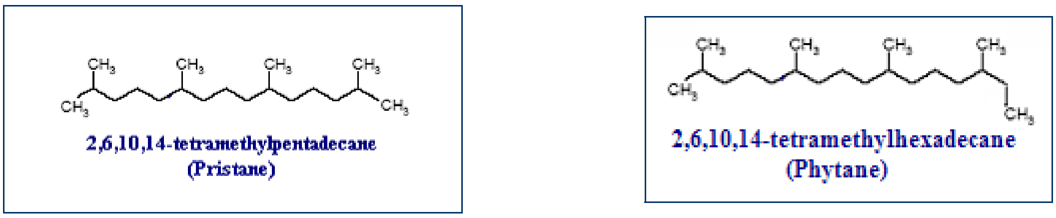

Figure 11 Pristane and Phytane Chemical Structures

The soils sample data for the fragmenotgram were reviewed for the ion 85m/z and the resulting fragmentogram was compared to the NIST library using the Time of Flight deconvolution software. The comparison indicated a 96% match to the library example of pristane (Figure 12)[7,9,10,23].

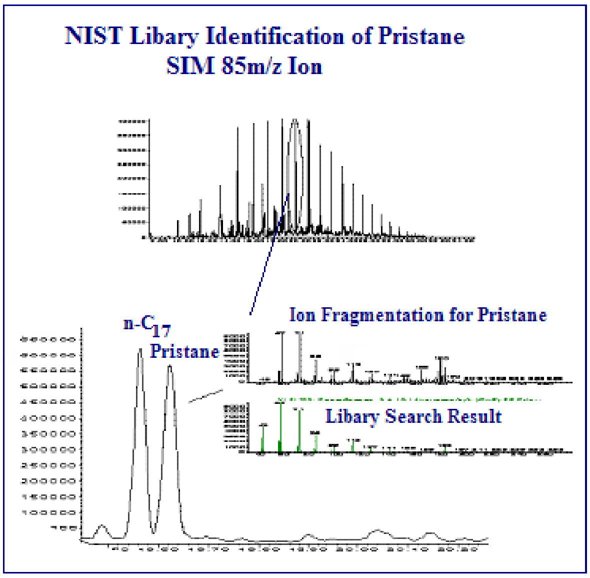

Figure 12 Pristane Identification – Soil

The presence of these markers confirms the addition of diesel to the contaminated site where the kerosene was spilled

2.3 LEVEL 3 – STATISTICAL ANALYSIS OF THE DATA

Having conducted Level 1 and 2 investigations, data obtained from both these procedures can be utilised in various mathematical routines to determine the degree of similarity to reference materials, degrees of weathering and / or biodegradation. Evaluation of those diagnostic ratios exhibiting considerable variability due to analytical variance and sample heterogeneity is determined using Compound Ratio Analysis Technique (CORAT).

3.0 COMPOUND RATIO ANALYSIS TECHNIQUE (CORAT)

In modern forensic investigations, various analysis techniques have been developed and applied to data interpretation. The application of sophisticated statistical analysis techniques for analysis is a relatively new phenomenon of which compound ratio plotting is one such approach. This is a dynamic area of research which enhances the interpretive power of hydrocarbon fingerprinting and promises to greatly improve the identification of spill sources. CORAT is a combination of analytical and interpretive techniques that utilises "fingerprint" chromatograms of crude oil samples used in the petroleum geochemistry industry. This technique has been adapted in this study to review the compositional variations of source specific PAH markers in the Tank reference product and compared to the contaminated Soil sample to try and determine whether the origin of the source of contaminant. Since a GC fingerprint is a representation of the relative concentrations of compounds present in a sample as analysed, it can be used for the relative abundances and distribution of each compound and then plotted on a star plot diagram. This technique assesses whether or not two or more products correlate by comparing the relative abundance of selected compounds obtained from the chemical fingerprint and rationing them to each other. Values for these ratios for each sample product are plotted on a polar CORAT star plot. On such diagrams the composition of each product is represented by a star in which each point on the star corresponds to the value for a given peak ratio (Kaufman *et al.,* 1990). Figure 13 reviews the differences between the kerosene which was found in the Tank and diesel in the soil samples which appears to be added after the initial spill. The star plots differ for the naphthalene series which suggests two possible sources of contamination at the site[7,10].

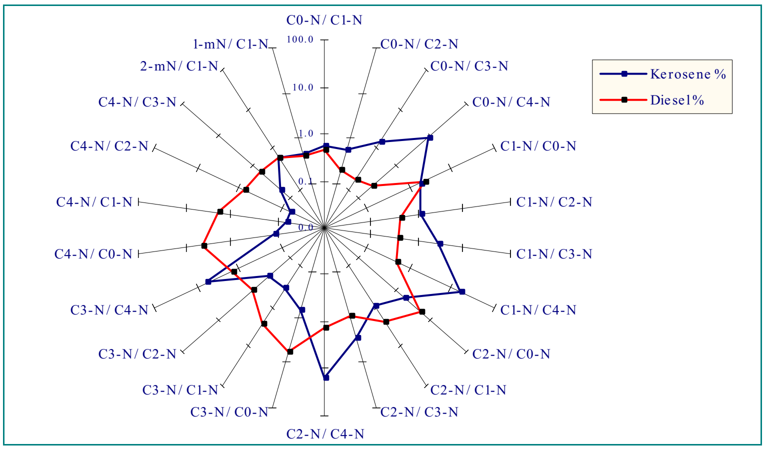

Figure 13 Naphthalene Series CORAT – Tank and Soil

4.0 CONCLUSIONS

The review of the Tank and Soil samples for the naphthalene, phenanthrene and dibenzothiophene alkylated series confirmed two sources of contamination at the spill location. The identification of the source specific markers found in diesel and the EPH chromatogram indicated the presence of this petroleum product.

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GROUNDWATER AND HEALTH ISSUES

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ABSTRACT

Groundwater is a valuable resource and must be protected for future use. In rural Ireland, groundwater is the source of many public water supply schemes and almost all the water serving individual dwellings and commercial premises. The majority of these premises are also served by individual or group wastewater systems that discharge to groundwater. Groundwater quality can be compromised by wastewater systems that are located on unsuitable or inadequate sites and not installed, constructed or maintained to an adequate standard.

Cryptosporidium and VTEC are enteric pathogens that are widespread in the environment and have been implicated in outbreaks of infectious disease in Ireland.

An aim in health promotion is to reduce cardiovascular disease in Ireland. Reduction of salt in the diet is one of the achievable goals in this strategy. Salt is used in some water treatment systems. Hard water is good for health.

1.0 INTRODUCTION

Groundwater is the major source of water supply in rural Ireland today. It is a valuable and vulnerable resource which must be protected for future use. Kildare County Council is currently developing four well fields with which to augment the Regional supplies. Many groundwater sources are uncontaminated and pathogen free, and comply with drinking and bottled water standards without the need for disinfection.

There are many groundwater topics that have inter-related health aspects including arsenic, farmyard waste and landfill through to uranium and wastewater treatment systems; however this presentation will be confined to the following areas of current health interest or topicality. The risks associated with the mode of transmission of two enteric pathogens, namely VTEC and Cryptosporidium, the continuing risk from wastewater treatment systems, the potential risk of contamination from domestic fuel oil storage and finally a discussion on dietary salt content.

2.0 ENTERIC PATHOGENS

Surface waters and groundwater may be contaminated by pathogens which originate in the faecal matter of infected humans, animals and birds. Reservoirs of infection exist in all human and animal populations therefore the risk of contamination is ever present. In Ireland the waterborne pathogens of concern include viruses, bacteria and protozoan. The protozoan pathogens are of special significance because of their environmental persistence and resistance to chlorination.

2.1 VTEC

Verocytotoxigenic Escherichia coli (VTEC) have emerged as a serious global public health concern in the 1980's. Escherichia coli are bacteria commonly found in the intestinal tract of humans and animals. There are hundreds of strains of E.coli most of which are harmless and do not cause illness, however some, including the group VTEC may cause serious illness and even death. There are many strains of VTEC of which E.coli 0157:H7 is the most common; it is the main cause of VTEC infection in Ireland. VTEC poses a serious risk to humans as the number of organisms required to cause illness is very low. It can survive the gastric acids in humans and pass to the intestine where it grows and produces toxins. The incubation period is between 1-8 days but is usually 2-4 days.

Epidemiology: VTEC occurs worldwide and is a serious threat to public health. The low infectious dose, the high morbidity and mortality associated with VTEC infection make it a high priority for public health action.

The most significant outbreak of E.coli 0157:H7 associated with groundwater occurred in Walkerton, a small town in Southern Ontario, Canada in May 2000. The drinking water system became contaminated primarily with E.coli 0157:H7 but Campylobacter jejuni was also implicated. Seven people died and more than 2,300 became ill. The primary, if not the only, source of the contamination was manure that had been spread on a farm (using normal farming practice). The contamination occurred after a five day period of exceptionally heavy rain. DNA typing of the animals and manure on the farm revealed that that the E.coli and Campylobacter strains on the farm matched strains that were prevalent in the human outbreak in Walkerton. The municipal water system was supplied by three groundwater sources. One of the wells was a shallow well; the casing extended just 5m below the surface. The water was drawn from an area of highly fractured bedrock 5-8m below the surface. The shallowness of the soil overburden and the nature of the bedrock allowed bacteria from the surface to quickly enter into a fractured rock channel and proceed directly to one of the wells. The outbreak would have been prevented by adequate chlorination of the supply. The use of continuous chlorine and turbidity monitors would have alerted the operators to the increased chlorine demand.

Laboratory procedures used in the identification and confirmation of VTEC include serotyping, phage typing and molecular typing. The improved ability to detect and identify the causative bacteria has enabled accurate trace back to the source of infection and is very valuable in the investigation of an outbreak.

Reservoirs of Infection: Livestock are the reservoir for most VTEC, with cattle considered to be the principal source of E.coli 0157:H7. VTEC is also present in the intestines of other animals including sheep, goats, deer, horses, dogs and cats. Seagulls, pigeons and geese are also known to be carriers. Infected humans will also shed the bacteria. The source of contamination is generally human faecal material or animal waste. Initially, VTEC was thought to be mostly foodborne or acquired from contact with animals but we now know that it is widespread in the environment. VTEC must now be regarded as part of normal gut flora of livestock. There is limited information concerning the prevalence of VTEC on Irish farms. However, it does appear that the elimination of VTEC in farm livestock and the environment is not an achievable goal. Risk reduction by good farm and waste management practices are the best methods of control.

Survival: The minimum temperature for VTEC growth is 7ºC and the highest is 44.5ºC with an optimum of 37ºC. Pasteurised milk is safe. The organisms survive at low temperatures and resist freezing. VTEC is tolerant of acidic environments and can remain viable in soils, water and manure for months. Chlorination is effective in eliminating this pathogen.

Symptoms: Infected persons who seek medical attention suffer from severe abdominal cramps followed by bloody diarrhoea. Usually, there is little or no fever and patients recover in 5-10 days. Sometimes the infection causes non-bloody diarrhoea or no symptoms. Those most vulnerable to infection are children under 5 years of age, the elderly, immuno-suppressed persons and patients with chronic illness. The symptoms resulting from the infection are more severe in these vulnerable groups. In some persons, the infection can cause a complication called haemolytic uraemic syndrome (HUS), in which red blood cells are destroyed, resulting in kidney failure. HUS is said to be the principal cause of kidney failure in children, with the majority of cases caused by E.coli 0157:H7 infection.

Water and Soil: VTEC has been detected in soil and water. Some outbreaks have resulted from the use of contaminated water in fruit and vegetable growing. Waterborne outbreaks have implicated both drinking water and recreational waters. Groundwater is vulnerable when influenced by surface water or when contamination is washed down particularly after heavy rain as in the Walkerton outbreak.

2.1.1 VTEC 0157 outbreak at a sports ground in Ireland 2004
A Brief Outline of the Incident and Investigation
In June 2004, an outbreak of VTEC was associated with a sports club. A total of four people were ill, with three hospitalised. The club hosted two competitions which were attended by about 900 people from all over Ireland. A confirmed case of VTEC was notified and the patient's food history indicated the sports club as a possible source of infection. The water supply to the club was from an untreated private well. The club immediately took precautionary measures to prevent consumption of the water, including the discarding of ice and this prevented further infection.

Subsequent environmental, microbial and epidemiological investigations indicated the consumption of well water from the sports club as the cause of the outbreak.

The four people ill were positive for VTEC (VT1 and VT2). Almost 700 people responded to a telephone questionnaire. The environmental investigation continued to try to determine the source of the contamination.

Well water: Well water samples were **positive** for VTEC (VT1 and VT2). No cause of contamination was identified. The well is located between a pitch and a training field. The well is a deep bore, steel lined to approx 6m. The water was not treated then but is chlorinated now. The pre-treated water has been free of VTEC since July 04.

Sheep had gained access to the pitch but are not normally allowed on the grounds. VTEC was found in animal faeces samples but it was a different strain.

Water from other wells and a quarry in the area were tested and all were negative for VTEC.

Water from a piped surface water drain was found to be **positive** for VTEC (VT1 and VT2) about this time. The source of this contamination is not known. Since then another strain of VTEC was detected in a further sample taken from a roadside gully leading to this piped drain.

Septic Tank: The club septic tank system is 60m away and down gradient from the well. The effluent from the septic tank was **positive** for the VTEC (VT1 and VT2). A dye test on the septic tank did not show up in the well or in the piped surface water drain.

2.2 CRYPTOSPORIDIUM

Cryptosporidium is a protozoan parasite of medical and veterinary significance. In 1976, it was identified as a human pathogen following investigation of illness in AIDS patients and is now recognised as a common enteric pathogen throughout the world. Cryptosporidium is a notifiable infectious disease in Ireland since Jan 2004. Increased reporting will lead to better surveillance and information on Cryptosporidium in this country.

Epidemiology: Cryptosporidium occurs worldwide and in all age groups. Young children are less likely to have had prior infection with Cryptosporidium than adults therefore the risk will be greater in this category. It is not surprising that the peak age of incidence appears to be in children aged 1-5 years. In developed countries, Cryptosporidium is one of the most common causes of infective diarrhoeal illness in humans. A study in England and Wales in 1996 found that Cryptosporidium was the third most common cause of infective diarrhoea after Salmonella and Campylobacter. A study conducted in Cherry Orchard Hospital, in 1987 found that 4% of admissions for gastroenteritis in children aged 14 years or younger were due to Cryptosporidium. The peak month for Cryptosporidium infection was April with a higher incidence in children from rural areas which was attributed to the lambing and calving season. A similar study in Galway, in 1987, found Cryptosporidium in 4.3% samples from children with acute diarrhoea. Prior to the introduction of special anti-retroviral therapy AIDS patients were at significant risk of acquiring the illness which then persisted and often contributed to the death of these patients.

The first reported outbreak of Cryptosporidiosis in Ireland that was strongly associated with drinking water occurred in April 2002. There were 26 confirmed cases. The water source was a spring-fed lake serving a population of 25,000. The water was chlorinated but not filtered. Heavy rain is thought to have facilitated the ingress of animal waste into the lake.

Infectious agent or Pathogen: Cryptosporidium is a coccidian protozoa associated with human and animal infection. There are many species of cryptosporidium. Until recently Cryptosporidium parvum was thought to be a single species with two distinct genotypes Type I (human) and Type 2 (bovine). C. parvum Genotype 1 is now reclassified as C. hominis. C. hominis is isolated almost exclusively from humans and is associated with human to human transmission. Genotype 2 is now known as C. parvum and may be isolated from animals such as cattle, sheep and goats. C. parvum can be transmitted from animals to humans; it can then be isolated from infected persons. C. hominis is thought to be more aggressive or virulent in humans with a longer period of oocyst shedding than C. parvum.

Reservoirs of infection: Cryptosporidium species have been found in humans, mammals, birds, fish and reptiles. C. parvum is predominately a parasite of young animals. The main sources of infection are thought to be calves and lambs with scours. Humans can be infected at any age and previous exposure tends to confer only partial immunity to subsequent infection.

Survival: The life cycle of Cryptosporidium is completed within a single host and it cannot grow outside an infected host. The parasite multiplies in the gastrointestinal tract and oocysts, 4-6 microns in diameter, are shed in large numbers in the host faeces potentially resulting in significant environmental contamination. The oocysts can survive for long periods in cool, wet environments. The oocysts are very resistant to chlorine as used in water disinfection but are inactivated by heat as in the pasteurisation of milk (71.7ºC for 15secs) and by bringing water to the boil. Water filtration is required to remove oocysts.

Symptoms: In humans the symptoms are a mild fever, abdominal cramp and diarrhoea preceded by vomiting in children. Asymptomatic infections are common and the parasite may continue to be passed for up to 2 months. The incubation period is not precisely known but is thought to be 1-12 days with the average about 7 days.

Water: Detection of Cryptosporidium in water is problematic as the small size of the oocyst, low concentration in the environment and the difficulty in separating them from other particles of the same size makes accurate enumeration difficult. The USEPA and Drinking Water Inspectorate in England and Wales have published methodologies for sampling and detection. The current precautionary practice is to count all oocysts found in water without determining viability. The laboratory typing of Cryptosporidium isolates can help to identify the source of infection in outbreaks. Further research is needed to improve tests to determine the viability and pathogenicity of oocysts in the environment so that the degree of health risk posed by oocysts in drinking water can be better assessed.

Cryptosporidium found in water does not invariably lead to outbreaks. There is no internationally recognised threshold level of Cryptosporidium contamination of water that indicates that human illness is likely to develop and the risk to health from Cryptosporidium in drinking water is not quantifiable. Dose size, parasite characteristics and the immunity of those exposed are all inter related. The UK is the only country that has put a mandatory limit for Cryptosporidium in water. The UK limit is 1 oocyst per 10 litres of water. The limit is set as an enforcement mechanism rather than on health grounds.

Cryptosporidium is normally associated with surface water supplies but has been associated with outbreaks in groundwater supplies. The supplies are thought to have been contaminated by wash down of animal slurries after periods of heavy rain. Where groundwater is influenced by heavy rain, turbidity detection meters/alarms should be installed to prevent turbid water entering the system. The installation of alarms is even more important in catchments where livestock are farmed intensively.

Risk Assessment: Risk assessments should be carried out on water supply sources as routine monitoring for Cryptosporidium is not practical. The Scottish Risk Assessment model for Cryptosporidium has been revised and published as "The *Cryptosporidium* (Scottish Water) Directions 2003". This model has been adapted by the EPA and is recommended for use in Ireland. The methodology is outlined in the EPA 2004 Publication "EC (Drinking Water) Regulations, 2000. A Handbook on Implementation for Sanitary Authorities". The method involves a scoring system for surface water and groundwater catchments taking into account a series of risk factors and the treatment provided. This risk assessment is only a part of a full risk assessment procedure.

Overall Conclusions: In order to reduce risk of infection with enteric pathogens:

- Recognise that VTEC and Cryptosporidium are ubiquitous in the environment and can survive in cool moist conditions including groundwater.
- Risk assessments should be carried out on all water supply sources.
- Good farm management of waste and soiled water is the best method of control.
- Animal access to water bodies used for human consumption should be restricted.
- Source protection is essential. The careful siting of well water sources and wastewater treatment systems is of the utmost importance.
- Practice very careful personal hygiene when dealing with young animals and animal waste.
- Water should be appropriately treated before consumption.
- Prompt action to stop consumption of contaminated water will prevent further cases of enteric infection.
- The improved detection methods enable the mode of transmission to be detected accurately.

3.0 RURAL HOUSES AND OTHER SMALL DEVELOPMENTS

Census 2002: The total number of private dwellings in Ireland recorded in the 2002 Census was 1,279,617. The numbers of dwellings served by individual wastewater treatment systems is stated as 416,715. The number of dwellings using an individual well source is recorded as 137,705. (See extract in Table below). In addition, premises such as hotels, golf clubs, nursing homes and factories would also use groundwater for their supply. The provision of public mains water supply to many rural areas has reduced the number of dwellings dependent on wells while the number using wastewater treatment systems is increasing and this will lead to increasing pressure on groundwater quality.

Extract from Census 2002 **Total Private Dwellings: 1,279,617.**

Water Supply	Town Dwellings	Rural Dwellings	Total	Sewerage facility	Town Dwellings	Rural Dwellings	Total
Public mains	722,509	215,256	937,765	Public scheme	729,962	92,612	822,574
Local Auth. Group Water	30,932	86,880	117,812	Individual Septic tank	382,987	24,781	407,768
Private Group Water	1,259	44,567	45,826	Other	2,522	6,425	8,947
Private source	2,723	134,982	137,705	No sewerage facility	622	6,514	7,136
No piped water	245	4,233	4,478	-	-	-	-
Not stated	25,196	10,835	36,031	Not stated	24,977	8,215	33,192

There is an increasing threat to human health and the environment from inadequate disposal of wastewater. Pollution of groundwater is hidden and it is only when systems fail or sewage ponds that any action is taken.

In order to protect groundwater planning permission for houses and developments should not be given on unsuitable sites. Problem sites include the following; sites that are too small, waterlogged sites and those with high winter water table levels, wastewater treatment systems too close to wells, too many houses and development in an area, inability of sub-soil to percolate and treat the effluent, unsuitable material used to in-fill land, etc. This list is not exhaustive.

The minimum guideline for separation distance to protect well water supplies is considered by many to be the maximum distance required with no allowance made for difficult site conditions. It is essential that there is increased control and enforcement of planning conditions. Systems should be constructed in the location and manner for which permission was granted. Site improvement works if needed should be carried out prior to the building being occupied. Sites are often landscaped so that non-compliance is hidden.

Systems must be constructed, installed and maintained to an adequate standard. Households should receive information and training in the operation of their wastewater treatment systems. Owners should be instructed on the nature of the biological treatment and on the household cleaning products which can be used without interfering with the process. The need for continued maintenance of the systems needs to be appreciated and the systems must be located so that they are accessible for maintenance and desludging. Outlets for sludge disposal is should be provided so that disposal is carried out safely.

Monitoring of groundwater can show elevated nitrate, ammonium, potassium and chloride concentrations long before any microbial contamination is detected and these parameters are a useful guide in indicating human influence on groundwater.

There is no requirement to prove that the well water supply is fit for human consumption except in commercial or public premises. Monitoring of well water supplies serving individual commercial premises under the Drinking Water Regulations in 2004 has highlighted water quality problems which included microbial contamination, water treatment systems not maintained, defective and leaking drainage systems. Managers of commercial premises have food management and many other skills but often lack expertise in maintaining water and wastewater treatment systems.

Contaminated well water supplies can result in social and community difficulties. People often suffer in silence as it may be a neighbour or local industry causing the pollution of the well while others may suspect that their water supply is contaminated but do not want to know.

Often the solution to contaminated groundwater is to bring a public or a group water supply scheme to the area to provide a potable supply. The groundwater contamination continues but is not monitored as the water is no longer used for human consumption. There is no pressure to remediate the groundwater by eliminating the cause and in many cases the contamination just gets worse. In fact, the provision of water mains in an area will result in much greater pressure to grant planning permission as the area is now considered “partially serviced”. In such circumstances site size is reduced, the number of systems increased thereby putting further pressure on groundwater quality.

The attitude that groundwater pollution does not matter as water can be treated to attain an acceptable standard for human consumption is very short-sighted since reversing the deterioration of groundwater quality may be difficult and expensive. Senior management in local authorities need to understand the long term significance of granting permission for development on sites which are unsuitable for wastewater treatment. The owners need to be educated in the sustainable management of their systems.

4.0 HYDROCARBONS

In a recent survey of wells serving individual houses and farms the storage of home heat oil and other fuel oil was a significant potential risk to groundwater. The outlet tap connection and feed pipe can leak and remain undetected. It is only when significant contamination has occurred that it will be detected in deep well water. It will be identified more readily in shallow groundwater sources. Sources are generally abandoned and remediation is difficult and expensive.

Recommendation: In order to reduce the risks associated with fuel oil storage improved design and guidelines with regard to better siting of tanks are needed.

5.0 SALT AND HEALTH

Water is treated for hardness in order to reduce deposits or scaling in domestic and commercial internal water distribution systems and appliances. Salt is used to treat water for hardness involving the exchange of calcium and magnesium ions with sodium ions. Studies have shown that hard water is generally good for health and in particular cardiovascular health. Hard water is considered a valuable resource in the equine industry in Co. Kildare as it contributes to good bone development and muscle strength. .

High blood pressure is one of the modifiable causal factors in the development of cardiovascular disease. High dietary salt intake is an important causal factor in the rise of blood pressure with age. Relatively modest reductions in salt intake have the potential to produce a significant fall in average blood pressure. The recommended dietary allowance (RDA) is 1.6g sodium (4g salt) per day for adults. One gram of sodium is equivalent to 2.54g of salt. Children should have a low salt intake. The benefit of salt reduction is likely to be most marked in the elderly because of the high risk of hypertension-related stroke and heart disease in this age group. Food is the most significant source of sodium in our diet. Sodium levels in water that has been treated with salt should also be taken into account when calculating the overall dietary intake.

The EC (Drinking Water) Regulations 2000 sets 200mg/l sodium as an indicator parameter level. The natural level of sodium in groundwater is generally very low however, in many waters treated for hardness using salt the level of sodium is close to or exceeds the parametric level

The EC (Natural Mineral Waters, Spring Waters and other Waters in Bottles or Containers) Regulations 2005 is the current legislation regulating the bottled water industry. The Regulations require producers to state "Contains Sodium" on the label if the mineral water is above 200mg/l. Mineral waters with sodium content less than 20mg/l may state "Suitable for a low sodium diet" on the label.

Recommendation: Hard water is good for health. A drinking water supply line should be provided for water consumption prior to treatment with salt for hardness. Sodium levels in water should be taken into account when calculating dietary intake.

6.0 CONCLUSIONS

Groundwater contributes to good health is the major source of drinking water in rural areas, is valuable, vulnerable and needs continued and improved protection. Universal education, information sharing, research, legislation and enforcement are all required in order to manage the risks and protect groundwater for future generations. Good interdisciplinary communication and teamwork is essential in the achievement of this goal.

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THE EFFECTS OF SEWER LEAKAGE ON URBAN GROUNDWATER SYSTEMS

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ABSTRACT

There is a growing body of evidence that sewer leakage is significantly degrading groundwater resources. Monitoring of the UK urban aquifers of Nottingham and Doncaster has highlighted frequent, though low level, occurrence of both bacterial and viral indicators of faecal contamination at significant depths in these systems. Application of other indicators (major minor ions, stable isotopes, age dating tracers) has confirmed sewers as the most probable source of this contamination and has allowed the preliminary quantification of this recharge component. This monitoring work on urban aquifers has underlined gaps in our knowledge of not only the flux of contaminants through the complex urban water system but also the fate and transport of pathogens once in the subsurface. Research aiming to achieve a better understanding of these issues is described here along with strategies to better understand the complex urban water system.

1.0 INTRODUCTION

The transmission of disease through contaminated groundwater resources is well documented (e.g. Hurst 1997; Macler and Merckle 2000). There are now known to be over 100 viral, bacterial and protozoan pathogens that can contaminate groundwater from faecal and other sources (Herwaldt *et al.* 1992). The storage and transmission of sewage in the shallow subsurface via septic tanks, soakaways and sewers present clear risks of faecal contamination of groundwater. This risk is exacerbated when such sanitation systems are poorly constructed or maintained. This threat to groundwater quality can result in the sanitation system failing to meet its primary role of breaking the faecal-oral transmission route of waterborne pathogens. Hence, urban populations dependent on groundwater for domestic use may be at significant risk of exposure to waterborne pathogens, above all if inadequate treatment of groundwater is undertaken. Such sources continue to be an important contributing factor to the occurrence of waterborne disease outbreaks (CDSC, 2000). This threat is a global one, especially given the fact that by late 2007 the majority of the world's population will, for the first time in human history, be urban dwellers (UN-HABITAT, 2003). Indeed, 3 out of every 4 Europeans live in an urban area and over 40% of the water supply of Western and Eastern Europe and the Mediterranean region comes from urban aquifers (Eiswirth *et al.,* 2003).

There is a growing body of evidence demonstrating that leaky sewers significantly affect groundwater quality. These come from both pipe engineering assessments and environmental degradation assessments. Pipe assessment work has found that sewers can permit significant quantities of exfiltration. Ellis *et al*. (2004) in a recent review of this work found typical exfiltration rates, both from test rig experiments and pipeline field investigations, to be of the order of ~3 to 5% of total annual sewer flow, though much higher rates have also been documented. Indeed any such pipe exfiltration estimates are very case-study specific and can vary within towns and/or neighbourhood depending on local pipe conditions, backfill material, role of self-sealing of defects via biofilm growth and sediment deposition, groundwater level etc. Here the composite effects of the sewer leakage effects are assessed via the environmental degradation approach by monitoring of urban groundwater quality.

A European Union 5FD initiative termed AISUWRS (Assessing and Improving Sustainability of Urban Water Resources and Systems) is currently addressing the issues of the quantification of sewer leakage impacts on groundwater and using this to compare leakage rates across a range of urban water supply and disposal scenarios via a Decision Support System for urban water management strategies (see www.urbanwater.de). In order to evaluate existing urban water systems and alternative strategies, the sources of contaminants, their flow paths and volumes (*e.g.* unaccounted-for-water, recharge from pipe leakage) and their sinks need to be identified for different urban settings. Robust indicators are vital in this chain and though there are many potential categories of sewage indicator (Table 1) cost and expertise dictated that inorganic chemistry, environmental tracers and microbiology were focussed on in the work outlined below.

Table 1 – Potential indicators of sewer leakage influence on groundwater and their associated constraints (modified from Barrett *et al*., 1999).

Category	Potential Indicator	Constraints
Inorganic major / minor ions	Metabolites (N, Cl), industrial effluents such as arsenic, silver	Multiple sources
Organics, pharmaceutical residues	Chlorinated solvents, THMs, BTEX, endocrine disrupters, clofibric acid	Analytical cost, non-specific to sewers
Detergent components	optical brighteners, boron, phosphate, EDTA, d-limonene, sulphur compounds	Rapidly attenuated in subsurface
Sewage-derived microbes	Bacteria, viruses, protozoa	Time-limited, sampling and analytical cost
Faecal steroids	Coprostanol	Rapidly attenuated in subsurface
Isotopes and environmental tracers	Nitrogen, Sulphur, Carbon isotopes CFCs, SF_6	Analytical cost, interpretation of results
Others	Iodated X-ray contrast media, caffeine,	Analytical cost

Compounding these threats to groundwater quality, urban aquifer management is complicated by the facts that there are variable dynamic distributions in hydraulic head due to complex abstraction patterns (Taylor *et al*., 2003) and often a multitude of abandoned boreholes in urban areas (Cronin *et al.,* 2003). This paper documents efforts to monitor and understand the extent of microbiological pollution in urban groundwater systems and to use other indicators to help quantify the degree of associated sewer leakage with case studies presented from the urban aquifers underlying Nottingham and Doncaster.

2.0 MICROBIOLOGAL MONITORING OF GROUNDWATER

Monitoring of groundwater quality is central to identifying potential risks to drinking water sources. Ideally, the occurrence and levels of all pathogens in drinking water should be monitored to restrict transmission of water-borne diseases. This ideal is, however, far from attainable. Many of the pathogens that are found in groundwater are highly infectious and represent a potential risk to health even when present in very low numbers. Most enteric viruses and protozoa usually require only 10 or less infectious particles or cysts to cause infection. However, bacteria do not usually cause infection unless more than 10^3 infectious cells are ingested (USEPA, 1992).

Pathogens and indicators in groundwater are either organisms in suspension or bound to colloids and so do not exhibit uniform concentrations, as do solutes. Hence, sampling regimes over short time periods leads to distinct changes in the levels of a particular organism. In these cases quarterly, weekly or even daily sampling may be insufficient to describe contamination events (Macler and Merckle, 2000). Sampling groundwater for the common bacterial indicators of faecal contamination normally requires the collection and analysis of a 100mL sample. The major difficulty in monitoring for viral and protozoan pathogens has been the need to use complex and specialised sampling methods to detect low concentrations of infectious particles in large volumes of water. The detection of potentially low numbers of virus particles consequently involves a preliminary concentration stage. Directed adsorption has become the preferred option for recovering viruses from large volumes of water (Hurst, 1997), and forms the basis of the standard method for enteric virus detection in water (APHA, 1998). Some recent studies (e.g. Powell *et al.* 2000) have successfully applied glass wool traps for the concentration of enteroviruses from large volume groundwater samples whilst in the field. These are the sampling methods used in the case studies discussed below.

3.0 CASE STUDY CITIES

Much research has been carried out in the Permo-Triassic sandstone aquifers in the English Midlands, one of the UK's most important public supply aquifers. In the past, these studies usually employed shallow monitoring piezometers and/or pre-existing deep abstraction boreholes (often of uncertain depth and construction). Large screened intervals and ambient vertical flow in such boreholes masks depth-specific trends through the mixing of waters from several horizons (Cronin *et al*., 2003). This deficiency in the ability to distinguish depth specific variations, led to the installation of three multilevel piezometers in Nottingham, two in Birmingham (Taylor *et al.,* 2003) and five in Doncaster (Rueedi *et al.,* 2004). All of the multilevel piezometers were installed in open holes 36 to 90m deep, drilled by air-flush and each has 5 to 10 sampling ports. Bentonite clay seals (1 to 3m thick) separate each sampling interval. The results from Nottingham and Doncaster results are focused on here.

Nottingham: The city is underlain by a sedimentary sequence (Carboniferous to Triassic) of limestones, marls, sandstone and mudstone that dip generally 1.5 to 4° toward the SE. The Sherwood sandstone is underlain by Permian marls and, in the southern and eastern areas, overlain by the Mercia Mudstone. Extensive Quaternary superficial deposits in the Trent valley consists of till, sand and gravel, silt and clay. The thickness of these deposits is generally less than 5m but can be up to 10m locally. Beneath much of the city of Nottingham the aquifer is unconfined and found at shallow depths. Regionally, groundwater in the Sherwood Sandstone flows toward the Trent River system. The multilevel sites are located in the unconfined part of the aquifer.

Doncaster: The Sherwood Sandstone has little topographic expression apart from isolated and subdued ridges on its western (basal) margin. The aquifer increases in thickness from its western edge, reaching about 175 m to the east of Doncaster where the city suburbs and nearby former coal mining villages are located. Quaternary superficial deposits ranging from glacial sand-and-gravel to peat and lacustrine silty clays overlie the sandstones in many places and these can exert a major control on recharge processes, flow patterns and solute/contaminant transport (Smedley and Brewerton 1997). Groundwater flow occurs from west to east following the artificial gradients induced by the water supply wells located outside the urban area. Four multilevel piezometers were located in Bessacarr-Cantley, a suburb of Doncaster. This area was chosen because it is located down-gradient of the historical town centre of Doncaster and because the Quaternary deposits are thin to non-existent across much of the suburb. The fifth multilevel is situated near Doncaster racecourse-immediately down-gradient of Doncaster town centre.

4.0 METHODS

Several indicators of faecal contamination (faecal coliforms, total coliforms, faecal streptococci, sulphite-reducing clostridia, coliphage, and enteric virus) were analysed for in Nottingham (June 2000 to August 2001) and in Doncaster (July 2003 to November 2004). Thermotolerant coliforms (TTC), faecal streptococci (FS) and sulphite-reducing clostridia (SRC) were isolated from 100mL sample volumes using membrane filtration and selectively enumerated by culture on membrane lauryl sulphate broth (TTC), Slanetz and Bartley agar (FS) and perfringens agar (SRC) respectively (Anon., 1994). The results from all analyses were recorded as colony forming units (cfu) per 100mL (membrane filtration). Field blanks and randomly selected duplicates were used as control procedures for all sampling rounds at all sites. All field blanks were found to be free of bacterial analytes. Enumeration of coliphage was determined by assay of 1mL of sample using a double agar layer technique. Two methods were employed for the analysis of enteric viruses (norovirus and enteroviruses) in sample eluates. Buffalo Green Monkey (BGM) kidney cells were used for the quantification of infectious enterovirus by plaque assay, both by the confluent monolayer and suspended cell culture methods (SCA, 1995). Viruses were also analysed using RT-PCR. PCR was used for the analysis of eluates for all other enteric viruses. Replicate 140 µL aliquots of each eluate were assayed with negative and positive controls included in each PCR set. All PCR products (RNA and DNA) were analysed by agarose gel electrophoresis stained with ethidium bromide. Field blanks were used as control procedures for all sampling rounds at all sites. All field blanks were found to be free of viral analytes. Results of coliphage are given as plaque forming units (pfu) while all others are given as colony forming units (cfu)/100ml.

Major ions were determined by ion chromatography whereas trace metals were analysed by ICP-AES and ICP-MS at the University of Sheffield and BGS Wallingford (Taylor *et al*., in prep; Morris *et al*., submitted). Charge balance errors in all analyses are less than 10% and commonly less than 5%. Stable isotopic ratios of N in groundwater were analysed by at University of East Anglia using the method of Fukada *et al*. (2004). δ^{13}C-DIC was analysed by mass spectrometry following the standard preparation method of acidification with phosphoric acid at Queens University Belfast and BGS Wallingford. Stable isotope ratios are expressed using the delta per mille (‰) notation relative to an international reference standard: δ_{sample} (‰) = $[(R_{sample}-R_{standard})/R_{standard}]*1000$ where R is the $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratio of the sample and international reference standard (Vienna Standard Mean Ocean Water for N, PDB Belemite for C).

Samples for CFC analysis were collected in autumn 2004 (Morris *et al.,* submitted) by the displacement method of Oster *et al.* (1996), without atmospheric contact in glass bottles contained within metal cans, while samples for SF_6 were similarly collected in glass bottles with conically-lined caps, according to the method of the USGS (Busenberg and Plummer, 2000).

5.0 RESULTS AND DISCUSSION

Table 2 – Summary of microbial indicator sampling numbers in Nottingham (3 multilevel piezometer sites) and Doncaster (5 multilevel piezometer sites) and percentages of positive detects from Nottingham (adapted from Powell *et al*., 2003) and Doncaster (adapted from Cronin *et al*., 2005)

	Nottingham N samples	**Nottingham % positive detects**	**Doncaster N samples**	**Doncaster % positive detects**
TTC	142	19	154	18
Total coliforms	Not sampled	Not sampled	154	34
Faecal Strep	142	23	154	40
SRC	82	68	154	44
Coliphage	112	6	154	1
Enterovirus	78	14	60	12

Table 2 summarises all monitoring results giving the total number of samples analysed as well as the percentage of positive detects of each parameter in both Nottingham and Doncaster. This table shows that sulphite-reducing clostridia has the highest number of positive detects for the Nottingham and Doncaster sites; in fact over 40% for both. SRC are anaerobic spore-forming non-motile bacteria exclusively of faecal origin that can survive in water for longer than coliforms or streptococci due to their spore-forming ability (Gleeson and Gray, 1997). Faecal streptococci, common in recreational water quality monitoring and as a comparison for TTC results, are the second most-frequently detected parameter in both case studies. Table 2 indicates high positive detect frequency of faecal indicators in the Permo Triassic Sherwood sandstone aquifer, though the actual values were generally at low levels and not indicative of gross contamination. However, the movement of even low levels of these microbes to depth is surprising from a hydrogeological viewpoint as the Sherwood Sandstone is generally regarded as a high-porosity, slow-moving system in the regional sense. However, the positive detects in Nottingham have been explained by a small but rapid flow component transporting sewer-derived leakage to depth (Cronin *et al*., 2003; Taylor *et al*., 2004; Figure 1). Preferential pathways such as fractures, fissures, and heterogeneities, and possibly abandoned boreholes, provide potential routes for microbial contamination to penetrate to depth quickly.

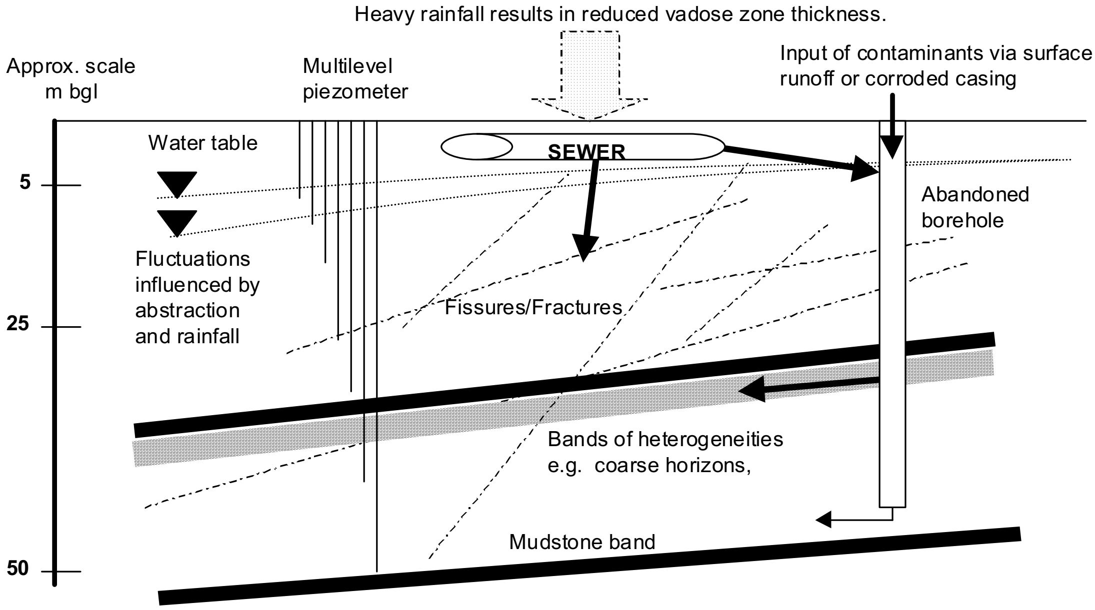

Figure 1**:** Conceptual diagram outlining possible routes for the transport of solute and microbiological contamination in urban aquifers (modified from Cronin *et al*., 2003)

These positive faecal indicator detects at depth have been supported in Doncaster by the use of the groundwater age indicators CFCs and SF_6 (Morris *et al.,* submitted). CFCs dating in urban areas can prove difficult because of contamination from localised sources (Oster *et al*., 1996) so SF_6, another trace gas resulting from post-war industrial activity, was also used because it is more rarely incorporated in groundwater at above-modern concentrations (Morris *et al*., submitted). Hence, the value of these tools in groundwater studies is either as dating agents or as indicators of contamination fronts. CFC and SF_6 have been found throughout the upper 50-55 m of the saturated aquifer in Doncaster, indicating that modern (<50-year old) recharge has penetrated to many tens of metres below ground level. These results have been explained by Morris *et al*., (submitted) as mixing of modern water moving via fractures in more highly cemented sandstone bands interspersed with the less indurated members.

Other evidence that sewer-derived recharge is adversely affecting groundwater quality comes from major and minor ion analyses. Taylor *et al*., (in prep.) clearly show the influence of sewer-derived solutes on urban groundwater quality. They employed the multilevel piezometers to map the solute depth profile of contamination in Nottingham and Birmingham. This revealed a penetration of anthropogenic solutes to depths of 47 mbgl and confirmed the contribution of exfiltrating sewers to urban recharge. Trace metals (Cr, B, Co) are similarly detected but in concentrations that reflect contamination from industrial land use, principally metalworking (Taylor *et al.,* in prep.).

Stable isotope ratios were used to constrain the origin of solutes from the wide range of potential sources that exist in the urban environment. Stable isotope ratios of N in nitrate ($\delta^{15}N_{NO3}$) trace the primary source of nitrate in concentrations, commonly exceeding the drinking-water guideline limit, to sewage. According to previous studies (e.g. Silva *et al.,* 2002) the $\delta^{15}N_{NO3}$ composition of groundwater impacted by sewage is reported to be in the range +7.3 to +16.9 % and for other N sources in the range -7 to+5 % for inorganic fertiliser and -3 to+8 % for soil organic N. At one of the two Nottingham multilevels sampled for $\delta^{15}N_{NO3}$, the resulting signatures throughout the hydrochemical profile ranged from +9.2 to +11.4 %; this is consistent with the range expected for sewage-impacted groundwater. Denitrification effects complicated the interpretation of the other Nottingham multilevel sampled for N isotopes (Fukada *et al*., 2004). $\delta^{13}C_{TDIC}$ signatures also proved a useful aid in resolving the principal influences on the geochemical evolution issues of urbanised Triassic sandstone groundwaters. Evolutions were found to be affected by both natural (carbonate and gypsum dissolution) and anthropogenic sources (mainly sewer-derived recharge). The combined application of groundwater pH, Total Dissolved Inorganic Carbon (TDIC) and $\delta^{13}C_{TDIC}$ helped to distinguish between these sources (Cronin *et al.,* in prep.). In Nottingham and Doncaster natural evolution involves an equilibration of recharging water with soil CO_2, having typical partial pressures of 0.0003-0.003 bar and $\delta^{13}C$ ratios between -23 and -27‰. Depending on the aquifer material, local dissolution of carbonate cements leads to progressively enriched $\delta^{13}C$ ratios. Admixture of sewage, however, is clearly distinguishable as it increases the TDIC and decreases the pH but has a minimal impact on $\delta^{13}C_{TDIC}$ due to the depleted isotopic value of the sewer exfiltration (typically <-19‰). The effect of sewage on the $\delta^{13}C$ ratio of recharging water, therefore, depends strongly on the local $\delta^{13}C$ signature of the soil CO_2 and the $\delta^{13}C$ signature of raw sewage. However, the qualitative nature o of $\delta^{13}C_{TDIC}$ means that it cannot be used in isolation to determine the extent of geochemical evolution but it can aid the understanding of natural and anthropogenic influences on urban groundwater quality (Cronin *et al*., in prep.).

Rueedi *et al,* (submitted) calculated the contribution of sewer leakage to total urban recharge using mass balance calculations from sewer and groundwater sampling results. Weekly precipitation data from the UK Meteorological Service (1970 to 2004) were used to obtain an average precipitation of 692 mm/yr with a large standard deviation of 114mm/yr. An urban mass balance flux model called Urban Volume and Quality model UVQ developed by CSIRO Australia (see Mitchell 2003) gave values for two components of the urban water balance (natural infiltration, sewer and storm water flow). Both the storm and sewer water systems were assumed to have approximately equal leakage rates, though different water qualities of course. The final recharge component, pressurized water mains, was estimated from hourly night-time flow records from Yorkshire Water in Doncaster which was subsequently corrected for actual water usage. 84% of the water mains pipes in the study areas of interest in Doncaster are between 25 and 50 years old. Most of the sewer and stormwater network are of unknown exact age but only a quarter of these systems are known to be less than 25 years old. The findings showed that even the deepest levels containing the oldest groundwater have a sewage-derived component of between 0 and 20mm/yr. corresponding to between 1 and 7% of the total urban drainage. The shallower wells, however, contain a sewage-derived component typically between 20 and 50mm/yr., corresponding to 5 to 12% of total urban drainage (Rueedi *et al.,* submitted). Similar mass balance calculations for Nottingham by Yang *et al*. (1999) using a GIS approach estimated sewer leakage to add ~10mm of recharge per annum.

6.0 CONCLUSIONS

Sewer leakage is evident from groundwater water quality monitoring of the UK urban aquifers underlying Nottingham and Doncaster. Frequent detects were found, though at low concentrations, of sewer-derived faecal indicators at depth in these slow-moving Permo-Triassic urban aquifers. Current strategies to protect the quality of groundwater sources that are based upon the natural attenuation of pathogenic microorganisms within wellhead protection areas defined by mean advective groundwater flow velocities and presumed pathogen survival times in the subsurface (30 to 50 days), may not be totally consistent with our knowledge of microbial transport and survival in the subsurface (Taylor *et al.,* 2004). Hence, even with protection measures, the vulnerability of untreated groundwater supplies to microbial contamination via the rapid transport of pathogenic microorganisms, particularly viruses, should be recognized. On-going tracing work at the Robens Centre and the University of Birmingham is looking at the use of non-pathogenic viruses (bacteriophage) as surrogates to better understand pathogenic viral transport and survival in the subsurface. Such work can better inform the mechanisms of microbial transport in the subsurface, such as the urban water monitoring work described above has highlighted. The complex urban water management issues raised by the findings are currently being tackled via the AISUWRS modelling suite. The ultimate aim of this work is to produce a Decision Support System to compare the affects of different urban water management strategies on groundwater quality and quantity.

7.0 ACKNOWLEDGEMENTS

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ADVANCES IN GEOPHYSICS - TIME-LAPSE RESISTIVITY IMAGING – LOCATION AND MOVEMENT OF LANDFILL PLUMES

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ABSTRACT

The leachate associated with landfill sites is characterised by low resistivity values. Consequently, 2D resistivity imaging is an excellent technique for locating former landfill sites and any associated contaminant plumes beneath the surface. The effects of the leachate associated with former landfill sites on the subsurface resistivity can still be determined even 20 years after they have been abandoned. Time-lapse resistivity imaging is capable of providing useful subsurface information. In addition, it has the potential for monitoring the migration of subsurface contaminant plumes. However, experiments have shown, that on a seasonal basis, an expected natural variation of up to 15% must be assumed. The variation of resistivity in 3 dimensions and the ability to produce areal "depth slices" is possible using 3D inversion techniques.

1.0 INTRODUCTION

Resistivity is a subsurface property which has been used extensively for subsurface investigations often associated with fluids and their movement e.g.

- Location of geological structures which control the movement of groundwater,
- detection the position of former waste disposal sites,
- investigation waste disposal sites for escaping effluent,
- location of pollutant pathways,
- map the extent of contaminant plumes,
- detection of salt water intrusions,
- investigation the integrity of barriers for seepage.

1.1 INTRODUCTION TO RESISTIVITY

Resistivity data can be collected using a 2D electrical imaging technique. Two dimensional electrical imaging allows the acquisition of apparent resistivity variations in both the vertical and horizontal directions. Electrical imaging is undertaken using an insulated multi-core cable with a number of fixed interval take-off points to which electrodes are connected. In this study, a 250 m long cable with 25 electrodes with take-off points every 10 m was used. This approach allows a maximum depth of 43 m to be investigated. The cable is connected to the resistivity meter which in turn is connected to a laptop computer which contains the relevant software to run the process. Once the resistance data are collected, they are processed in order to yield apparent resistivity values. These data are then modelled to determine how the true resistivity varies with depth using the RES2DINV inversion program.

2.0 WASTE DISPOSAL SITES

Although published resistivity values for subsurface substances encompass many orders of magnitude (see Gibson and George, 2004), the range for in situ substances is considerably lower. The leachate released from landfill sites produces very low resistivity values, typically less than about 15 ohm m. This contrasts well with glacial sediments and soils which generally are associated with higher resistivity values, 50-400 ohm m. The resistivity of rocks is dependent on rock type, porosity, permeability, degree of fracturing and amount of water present. It is generally within the 700-4000 ohm m range. The resistivity of air filled cavities is dependent on the size of the cavities but they are generally associated with high values, >15000 ohm m.

Figure 1 shows a 2D resistivity section across a former landfill site which has no surface expression and has not been used for 15 years. The natural background resistivity is shown in the red-pink colours and is in the range 800-1500 ohm m. The location of the former landfill site is clearly delineated by the blue low resistivity zone. Seepage of leachate from below the landfill has extended to depths of 32 m and is shown by the green-yellow colours. Figure 2 shows another section across the same site but at a different locality. The resistivity pattern is similar though in addition, a contaminant plume can be seen near the surface.

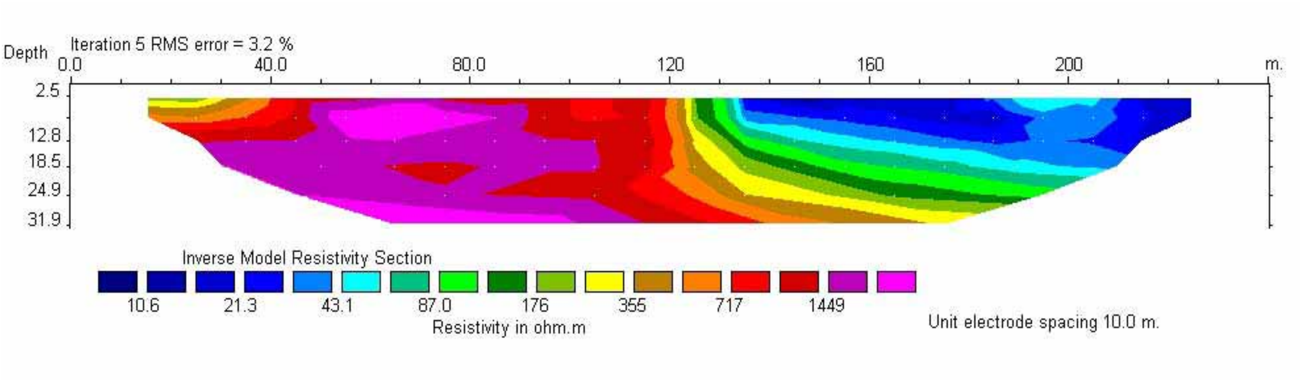

Figure 1: 2D resistivity section across former landfill site.

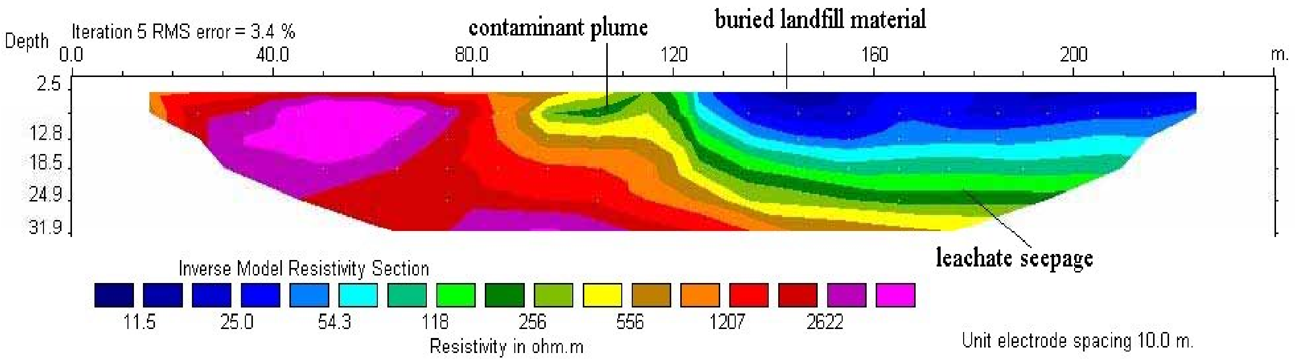

Figure 2: 2D resistivity section across former landfill site showing a contaminant plume.

3.0 TIME-LAPSE RESISTIVITY IMAGING

Time-lapse resistivity imaging entails the collection of data along the same traverse but at different times. Such an approach can be employed to map the migration of a contaminant plume. Leachate is associated with relatively low resistivity values and a percentage decrease in the resistivity may be interpreted as an indication of the spread of the plume. However, other factors have to be taken into consideration before it can be assumed that a subsurface change is due to the movement of a plume. A number of questions are posed:

- How does the natural subsurface resistivity vary at different times of the year or on the same calendar date but in different years?
- If temporal variations do occur, what is their range and are they uniform?

An experiment was conducted over a 3 year period (from September 2001 to September 2004) by collecting data at the same location at approximately 3 month intervals in order to address these questions. Figure 3 shows the percentage change in resistivity for a number of 3 month time periods. As expected, there are seasonal changes in the subsurface resistivity. However, the changes do not follow a simple pattern because in some 3 monthly periods there is mainly a decrease or mainly an increase or approximately equal increases and decreases. In terms of yearly changes, the greatest variations appear to be in the December to December time frame. Natural variation on a 3 monthly cycle indicate that changes greater than 10% are not very common, thus in any investigation a seasonal change of 15% should be assumed. Thus any changes less than 15% should be considered natural variation and not related to, for example, the movement of a contaminant plume. Yearly variation tends to be less than the seasonal (3 monthly) variation.

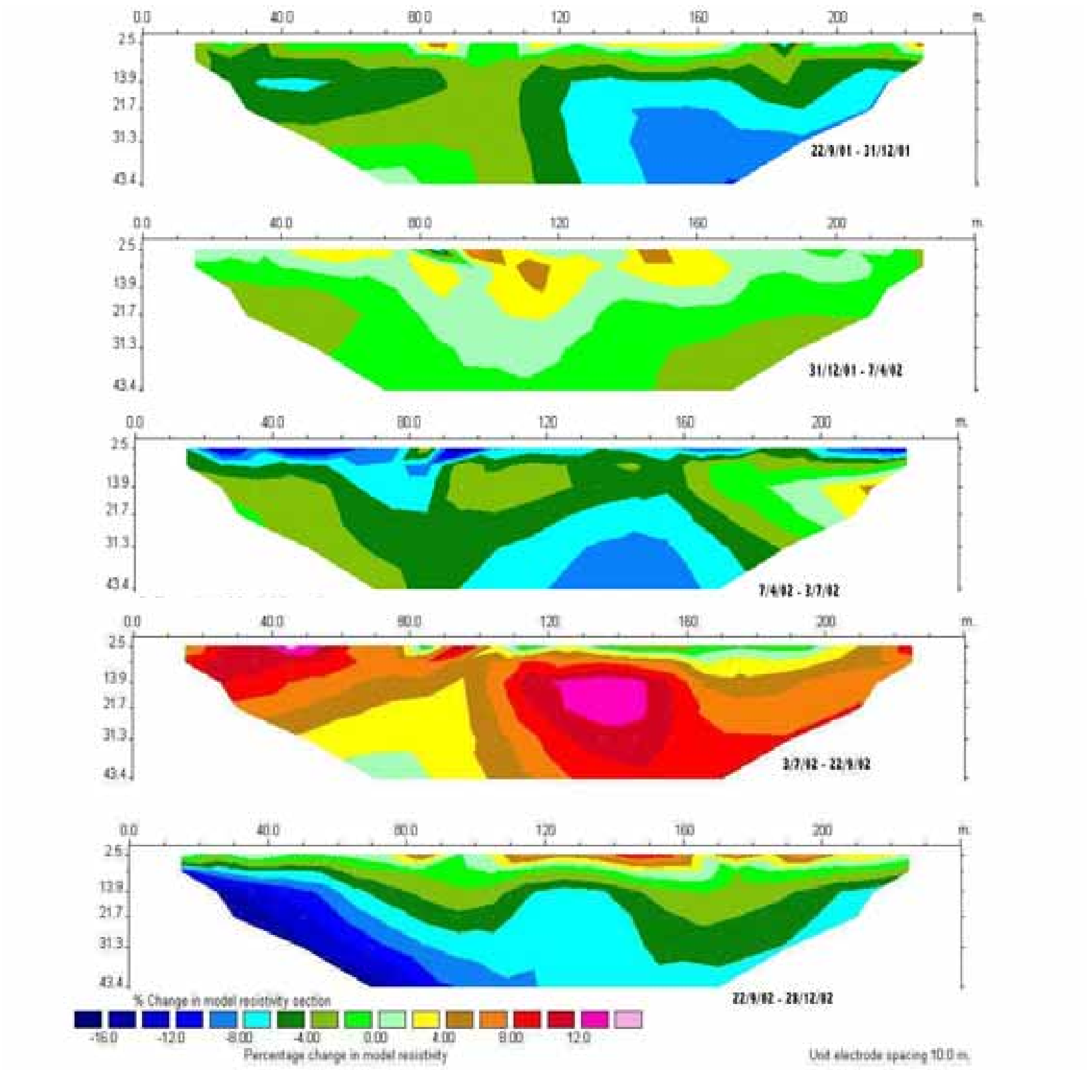

Figure 3: Percentage change in resistivity for a number of consecutive 3 month intervals for same locality.

4.0 2D AND 3D VISUALISATION OF RESISTIVITY DATA

Whilst Figures 1, 2 and 3 enable a resistivity section to be viewed, a better representation of subsurface resistivity variations can be obtained by performing a 3D inversion of the data. The results can then be digitally "sliced" to reveal more information. Figure 3 shows the areal variation in resistivity at 2 different depths. The left hand image is characterised by a range of discrete individual anomalies and no distinct pattern can be observed. However, the right hand image, taken at a greater depth shows the presence of two parallel features which are both associated with high resistivity values. The same data can be viewed as a 3D block or as slices with different orientations through the block, Figure 4.

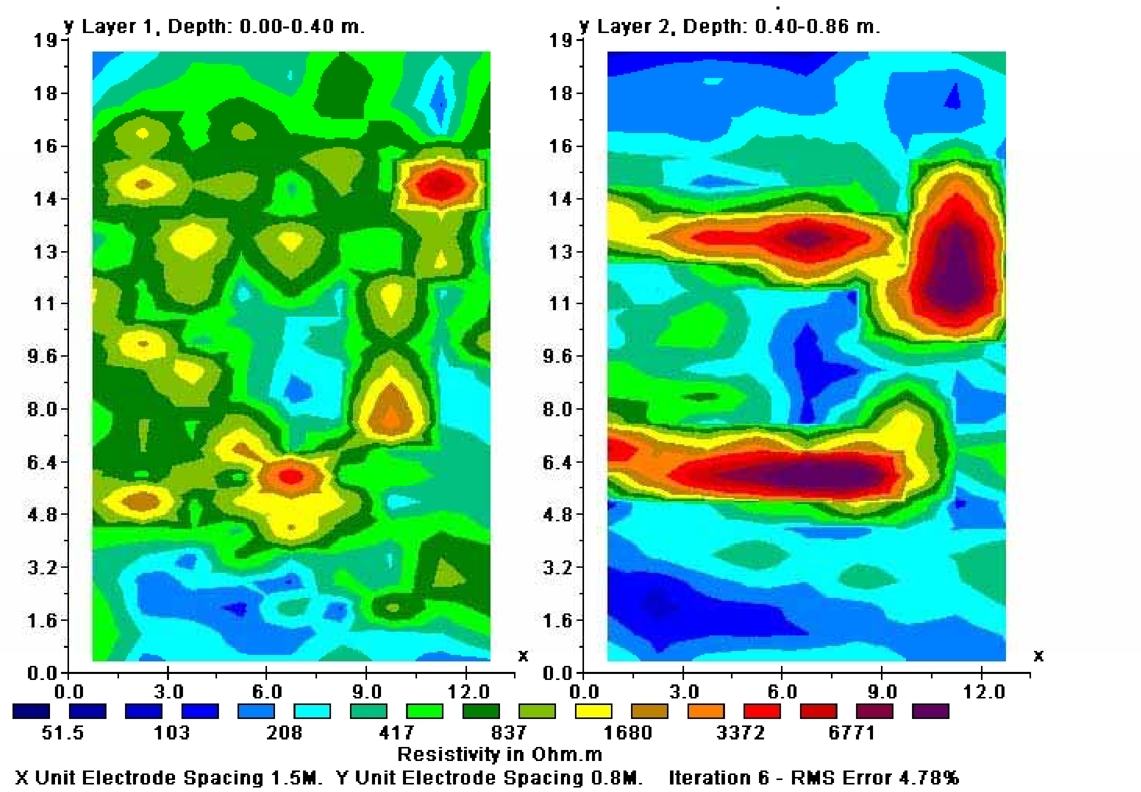

Figure: 3: Areal variation of resistivity produced by 3D inversion.

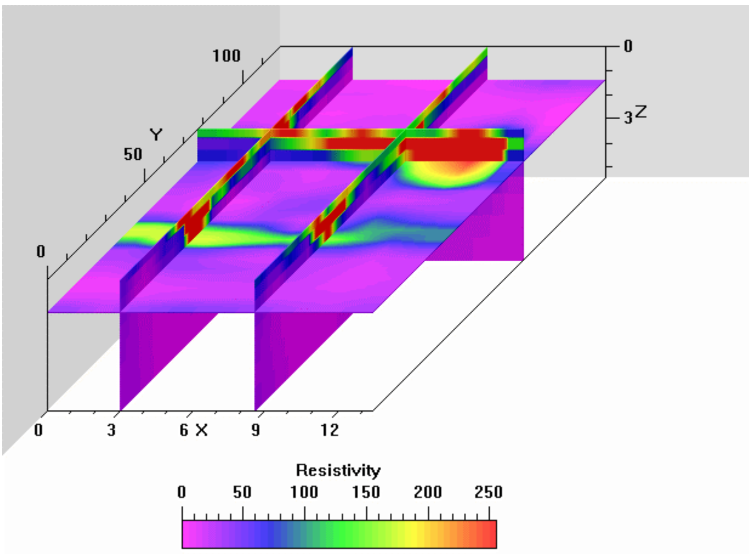

Figure 4: Fence diagram showing resistivity variations.

5.0 CONCLUSIONS

- 2D resistivity imaging is an excellent technique for locating landfill sites (either legal or illegal!) and any associated contaminant plumes beneath the surface due to the very low resistivity values associated with leachate.
- The presence of former landfill sites can still be located even 20 years after they have been filled in.

- Time-lapse resistivity imaging may prove useful for providing subsurface information and for monitoring the migration of subsurface plumes but a natural variation of up to 15% must be assumed.
- 3D inversion of resistivity data allows areal variations to be investigated.

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EVALUATING THE IMPACT OF GROUNDWATER ABSTRACTION ON SURFACE WATER FEATURES

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ABSTRACT

The thesis of this paper is that, whilst there have been few significant theoretical developments in the understanding of groundwater abstraction impacts on surface waters in the last 25 years, the range of tools for analysing such problems that are available to hydrogeologists is now substantial. Most recent advances in this area have been largely practical, relating to the development of new tools for collecting increasingly detailed data sets and the exponentially increasing computer power available for processing and modelling these data. This paper reviews the way in which the latter has allowed some of the theoretical/academic methods developed in the mid 20th Century to be developed in ways which make them accessible as general water resource management tools for the wider hydrogeological community today. In all this work, the guiding hand of an experienced hydrogeologist is still viewed as being essential: first to develop the conceptual understanding of the local groundwater – surface water system and then to determine how the effects of the simplifications inherent in any analytical or numerical model can be minimised.

1.0 INTRODUCTION

Is there any thing whereof it may be said, 'See this is new?' It hath been already of old time, which was before us. And there is no new thing under the sun. Ecclesiastes I 10, 9.

The thesis of this paper is that there have been few significant new theoretical developments in the understanding of groundwater abstraction impacts on surface waters in the last 25 years. Most recent advances have involved in the development of new tools for collecting increasingly detailed data sets and have taken advantage of the exponentially increasing computer power available for processing and modelling these data. Much of the work in this area has been driven by the need to comply with increasingly prescriptive regulatory regimes and, with the advent of the Water Framework Directive, this is set to continue.

This paper reviews the way in which the increasing amounts of PC power that are now cheaply available have allowed some of the theoretical/academic methods developed in the mid 20th Century to be developed in ways which make them accessible as general water resource management tools for the wider hydrogeological community today. Emphasis is placed on the need for a sound conceptual understanding of the local groundwater and surface water flow systems. Groundwater-surface water interactions can be considered to be relatively simple at a broad scale, but increasingly complex at the finer scales required to make the detailed management decisions that are demanded today. The various tools described here are simply that: tools that experienced hydrogeologists can use to make balanced decisions about how groundwater abstraction can be maximised whilst minimising the impacts on the environment and other users.

2.0 CONCEPTUAL MODEL

2.1 THE IMPORTANCE OF A CLEAR CONCEPTUAL UNDERSTANDING

Any attempt to evaluate the impacts of groundwater abstractions on surface water features must first invoke a conceptual model of the interaction of groundwater and surface water. The conceptual model needs to be appropriate to both the site setting and the nature of the questions being asked.

For instance, when examining the long term average impacts of groundwater abstraction on total catchment outflows, the conceptual model can be very simple: effectively the catchment is a 'black box' and the impact on flows is equal to the consumptiveness of the abstraction relative to the catchment[2]. Whilst simple, this analysis is very powerful, in that it immediately tells us that the answer to this particular question lies not in the hydrogeology of the catchment but in a careful analysis of the fate of the abstracted water. To some extent, this simple lesson is only now being widely acknowledged in water resource assessments: the importance of understanding rates of leakage from mains pipes and sewers and the rate and location of sewer discharges is now an important part of these studies.

When considering impacts at a sub catchment scale, a clear conceptual understanding of the local hydrogeology becomes much more important. This is discussed below under two headings: timescales and spatial distribution.

2.2 TIMESCALES

As groundwater flows through an aquifer, variations in the input (principally recharge) are attenuated to an extent that is dependent on the nature and size of the aquifer. This explains why baseflow is so important for maintaining summer flows in rivers: the large fluctuations in rainfall from day to day and month to month are smoothed out, leading to a discharge that is much closer to the long term average. As baseflow is so significant for maintaining summer flows, it follows that impacts of groundwater abstraction on baseflow are of most significance during this period. Coincidentally, the largest impacts from surface water abstraction typically occur during this period as well. From this it can be seen that understanding the factors that control the variation of baseflow (and impacts from groundwater abstraction) with time is important. This is particularly the case when groundwater abstraction rates vary seasonally but, even for constant rate abstractions, it is important as, for some aquifers, it may take many years before the impacts of a new groundwater abstraction are fully felt on surface water flows.

2.3 SPATIAL DISTRIBUTION

It is clear from both theoretical considerations and practical experience that the distance between a groundwater abstraction and the main points of groundwater discharge is very important for determining the timing of impacts. Abstractions near to rivers will, in general, have impacts that are closer in scale and timing to the actual abstraction than abstractions located at greater distances. Unfortunately, the widespread practice of locating abstraction boreholes near to rivers (due both to anticipated increased transmissivities in formations such as the Chalk and smaller pumping heads) means that much of the potential capacity of the aquifer to attenuate these impacts is often wasted. There have been some cases of abstraction licensing policies that attempt to 'band' abstractions with distance from the river (e.g. North East Region of the Environment Agency of England and Wales in the 1980s and 1990s). However, this type of approach has not been common.

2.4 AQUIFER RESPONSE FUNCTION

Erskine and Papaiannou, 1997 present an analysis of the key parameters that affect the attenuation of the recharge signal as it flows through an aquifer[3]. Whilst their analysis is focussed on a 1D conceptual model, it captures most of the factors that are relevant to most aquifers. Their analysis shows that the degree of attenuation of a variable recharge signal as it is translated into a varying rate of baseflow is controlled by two factors:

1. The aquifer diffusivity (transmissivity divided by storage coefficient). Aquifers with higher diffusivities are more 'flashy' in nature and provide less attenuation; and

[2] There are some conditions in which this may not be strictly true. Abstractions that lower the water table in the riparian zone may thus reduce the amount of evapotranspiration in the catchment which will marginally increase the amount of water available.

[3] Their analysis was one of the outputs of a research and development project funded by the Environment Agency of England and Wales to develop simple tools for examining issues of timing and distance from rivers on impacts of groundwater abstraction. A similar solution was derived by Oakes and Wilkinson (1972).

2. The length scale of the aquifer perpendicular to the river. Larger aquifers attenuate the recharge signal more strongly and have a more constant rate of baseflow discharge than ‘shorter’ aquifers.

They combined these two parameters into an ‘aquifer response function’ and showed how, for a 1D aquifer, some general rules about the attenuation of a sinusoidally varying recharge signal could be derived.

2.5 THE SIGNIFICANCE OF PROPERTIES NEAR TO THE DISCHARGE POINT

Whilst the aquifer response function is derived for a homogenous 1D aquifer. Erskine and Papaiannou also used simple numerical models to explore the effects of more ‘natural’ variation patterns in recharge signals and also the effect of lateral heterogeneity in aquifer properties. An important conclusion of this work was that, in heterogeneous aquifers, the aquifer diffusivity close to the point of discharge had a proportionally greater effect on the effective diffusivity of the whole aquifer than the diffusivity of the bulk of the aquifer.

This point is significant because,

- in the vicinity of most rivers groundwater flows are predominantly vertical;
- the geomorphology of most streams and rivers is very complex and dynamic. Figure 1 illustrates some common contributors to this complexity;
- ‘effective’ transmissivity along a groundwater flow line is strongly affected by thin but low permeability horizons (due to the harmonic mean approach to ‘averaging’).

These effects combine to suggest that groundwater-surface water interaction (and hence the effects of groundwater abstraction on stream flows) are unlikely to be linear systems and may be difficult to quantify using only information derived from the main body of the aquifer itself.

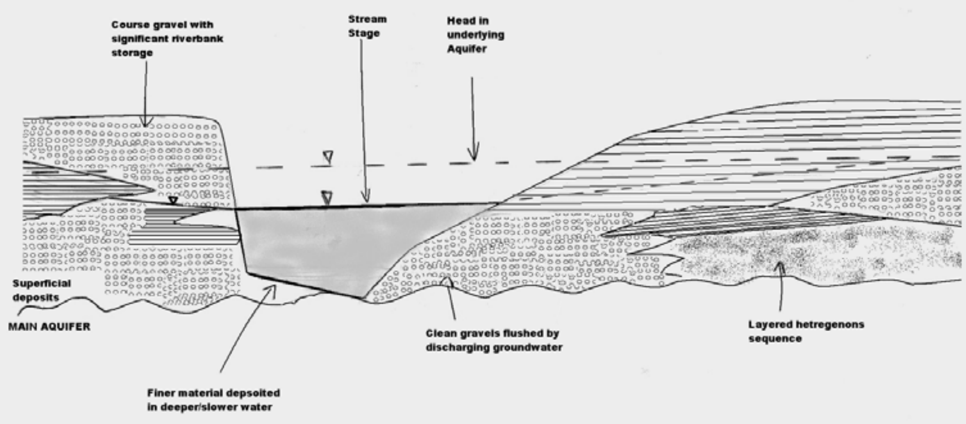

Figure 1 Example Stream Setting

2.6 SUMMARY

Whilst the discussion presented above indicates a need for caution in applying generalised solutions to particular problems in this area, it need not be a cause for complete scepticism about the possibility of learning anything about the likely scale and distribution of groundwater abstraction impacts on surface waters. In the following sections I present a brief summary of some of the main techniques available for quantifying such impacts, first by using analytical solutions and then by using numerical techniques.

3.0 ANALYTICAL APPROACHES

As discussed above, the interaction between rivers and groundwater systems is complex. Analytical solutions provide well-established, rapid idealisations of reality and which can be used for scoping calculations to determine the likely range of potential impacts and the key parameters that contribute to the uncertainty in any predictions. However, the experience and judgement of the user are important in determining their effectiveness.

Analytical solutions for common hydrological and hydrogeological problems are published regularly in the academic press and, due to the similarities in the underlying issues and available mathematical approaches, it is not uncommon to find identical solutions being re-derived at regular intervals.

One of the early quantitative hydrogeologists was C.S. Slichter, who was a professor of mathematics and later the dean of the Graduate School at the University of Wisconsin (Wang 1987). Slichter used potential theory to quantitatively describe the steady-state flow field in response to a discharging well (Slichter, 1899). He was one of the first to recognize that "the solution of any problem in the motion of groundwater depends upon the solution of [Laplace's] equation . . ." (Wang 1987).

The three most generally applicable analytical solutions for quantifying the impact of groundwater abstraction on river flows are those of Theis (1941), Hantush (1965) and Hunt (1999)/Stang (1980). As discussed above, the nature of the materials in the immediate vicinity of the stream is one of the most important parameters for determining the timing and location of groundwater impacts. These three solutions can principally be distinguished by differences in the way in which they consider this part of the system. The conceptual models used by the three solutions are shown on Figure 2 (note that all three models neglect vertical flows and that therefore the river could be represented as fully penetrating the aquifer. This has been omitted from the figures for clarity).

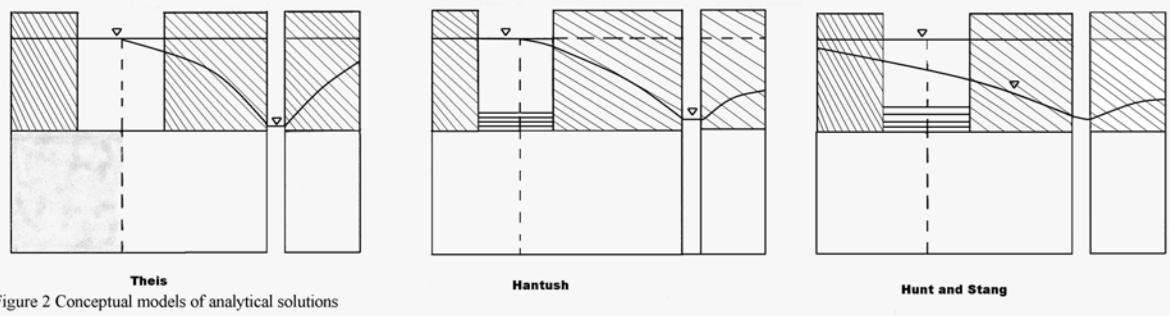

Figure 2 Conceptual models of analytical solutions

- o Theis (1941) makes assumptions which are equivalent to a fully penetrating river with no intervening low permeability stream bed sediments. This makes the solution conservative with respect to the rate and scale of the development of impacts near to the river. However, because the groundwater abstraction is rapidly balanced by inflows from the nearest stream reaches, this may underestimate drawdowns and impacts at greater distances.
- o Hantush (1965) also assumes that the head in the aquifer is equal to the stage of the river at the river (no water taken from storage on the far side of the river), but allows it to fall across the river bank sediments. He assumes that there is a zone of low hydraulic conductivity material adjacent to the river characterised by a river bank hydraulic conductivity and thickness, and a depth.
- o The Hunt model (Hunt, 1999) represents the river flow depletion due to a partially penetrating river with accessible storage on both sides of the river. (Hunt's solution for the river flow depletion was inferred by Stang 20 years earlier (Stang, 1980) using a symmetry argument

applied to Hantush's solution, but Stang did not derive the solution for drawdown away from the line of the river.)

Hunt assumes that there is a zone of low hydraulic conductivity material beneath the river characterised by a river bed hydraulic conductivity and thickness, and a width. The model assumptions are:

- o there is flow from the river to the aquifer through the river bed due to a difference between the river stage and the aquifer head;
- o the aquifer is saturated beneath the river bed, flow is horizontal and there are no vertical head gradients; and
- o the river is narrow (can be taken as a line source): the river width is only used to compute the resistance of the river bed sediments.

In order to quantify the development of impacts from finite or periodic periods of pumping, these solutions may be superposed. This solution has been published by both Glover and Balmer (1954) and Jenkins (1968) in the case of the Theis solution. The analogous superposition has recently been incorporated for the other solutions (Impact of Groundwater Abstractions on River Flows IGARF v1 – see Kirk and Herbert, 2002).

More recently, ESI has developed the IGARF approach further for the Environment Agency of England and Wales so that two-river systems and bounded aquifers can be considered (IGARF v4 User Manual. ESI, 2004). This uses an analogous approach to that used by Hunt for a single river, by evaluating the general drawdown solution using numerical inversion of the transforms. The inversion techniques use Stehfast's method for the Laplace transform (Talbot, 1979) and a Fast Fourier inversion for the Fourier transform.

Figure 3 shows some of the outputs that are available by using this approach for the different solutions described above.

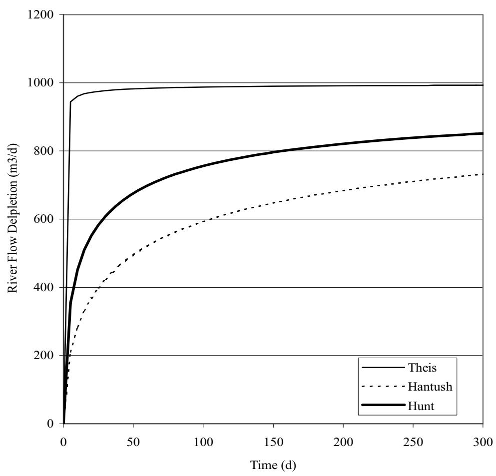

Figure 3 a Evolution of River Flow Depletion With Time

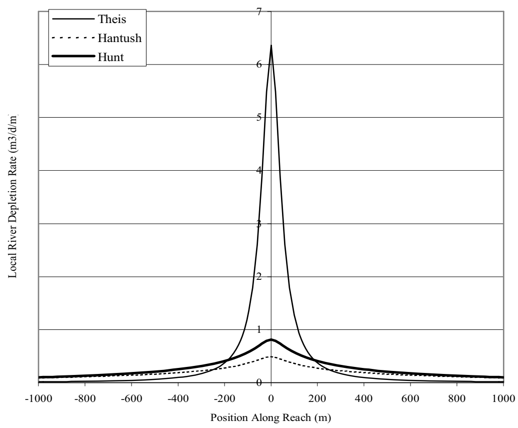

Figure 3b Profile of Flow Depletion Along River

The principle of superposition allows a wide range of combinations of analytical techniques to be developed and this is not discussed further here. An alternative approach to achieving some degree of spatial heterogeneity is to divide the study area into water balance polygons to which recharge, fixed heads, abstractions etc can be applied and the flow between the polygons is calculated using appropriate equations. A variety of solvers now available for EXCEL allows this problem to be set up and solved using spreadsheets.

4.0 NUMERICAL APPROACHES

4.1 SPATIALLY DISTRIBUTED APPROACHES

There are a wide range of finite element and finite difference codes available for numerical modelling of groundwater systems and I will not attempt a review in this paper. Perhaps the most widely used code is MODFLOW (McDonald & Harbaugh, 1988) and this has been the standard for water resource groundwater models in the UK for more than a decade. In this period there have been relatively few developments in the code itself. The main changes have been in the amount of computing capacity available which has allowed the standard grid size of these models to be progressively refined from 1 km which was typical 10 or 20 years ago to 250 m commonly applied today. This refinement has also been supported by increasing amounts of detailed data for the systems to be modelled. Detailed stream flow accretion profiles along rivers have been particularly important in this respect, but the long time series available at most river flow gauges (typically over 20 years) has also allowed the models to be validated against a wide range of climatic conditions.

4.2 TIME SERIES ANALYSIS APPROACHES

The analytical solutions described above all assume an isotropic and homogenous aquifer. The spatially distributed numerical models allow some degree of heterogeneity but, even with modern computing power, this is unlikely to be adequate to describe a karstic system in the level of detail required. This is due not only to the spatial complexity but also to the fast response time of these aquifers (very high diffusivities) which means that models would need much higher temporal as well as spatial resolution to avoid numerical errors. Furthermore, even if such a model could adequately reproduce the outflows from such a system, the degree of model equivalence is such that any predictions of future impacted states should be treated with some caution unless a careful sensitivity analysis has been carried out.

An alternative approach is to simulate these systems using 'black box' time series analysis approaches that are more common in hydrology. The idea is to attempt to simulate a baseline spring discharge time series (for instance) using only meteorological inputs and an understanding of the catchments and traced connections. If this approach is successful in simulating the key data features of the system (e.g. outflows), then this can be used to continually generate new 'baseline' data series against which actual data can be compared and the degree of impact measured. An example of this type of system is illustrated in Figure 4.

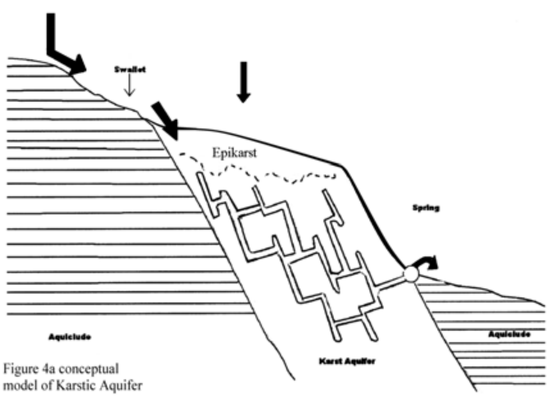

Figure 4a conceptual model of Karstic Aquifer

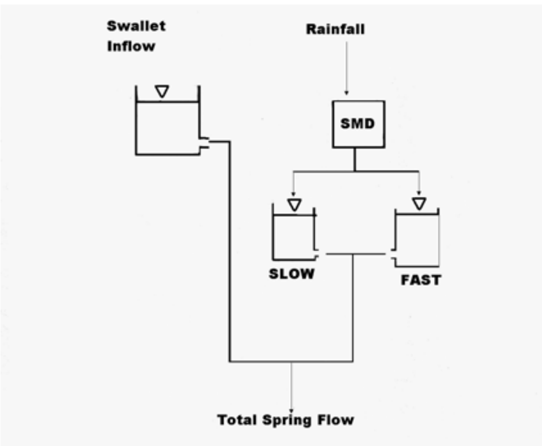

Figure 4b 'Black Box' Model of Karstic aquifer

5.0 CONCLUSIONS.

In this paper I have shown by means of examples that, whilst most of the fundamental techniques required to analyse groundwater-surface water interactions have been 'available' for many years, increasing amounts of PC based computing power mean that these can now be applied in most offices. The main pre-requisite is the guiding hand of an experienced hydrogeologist to develop the conceptual understanding of the local groundwater-surface water system and to determine how the effects of the simplifications inherent in any analytical or numerical model can be minimised.

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Session V

River Basin Developments

RIVER BASIN DISTRICTS – OVERVIEW OF SCOPE AND RESULTS FROM ALL COMPONENTS OF THE WFD

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The information contained in the paper and presentation is based on Ireland's Article 5 Characterisation Report (April, 2005), which was prepared by the joint collaboration of all members of the National Technical Co-ordination Group. The paper includes contributions from the Geological Survey of Ireland, the Environmental Protection Agency and Ireland's River Basin District Projects.

ABSTRACT

December 22, 2000, will remain a milestone in the history of water policies in Europe: on that date, the EU Water Framework Directive (WFD) was published in the Official Journal of the European Communities and thereby entered into force. The WFD establishes a framework for the protection of all waters including rivers and lakes, estuaries, coastal waters and groundwater with the overall objective of achieving at least good status for all waters by 2015. In Ireland, the main vehicle for delivering the objectives of the WFD is through the establishment of major River Basin District Projects, funded by the Irish National Development Plan, and outsourced to experienced Consultants. This paper outlines Ireland's approach to the implementation of the WFD at River Basin District level. The WFD requires the preparation of an Article 5 Characterisation Report for every EU River Basin District (RBD) by December 2004. This paper focuses on the key issues encountered during the development of Ireland's RBD Characterisation Report, focusing on the approach to the delineation of water bodies and undertaking risk assessments.

1.0 INTRODUCTION

"Water, water, everywhere……but not a drop to drink." The importance of water for life and as a key to development is becoming increasingly clear. Not convinced? Just stop to think for a few moments how your life would change without an adequate supply of clean water. As the demand for water for domestic, industrial, and recreational purposes increases so also does the need to protect it to ensure an adequate supply of clean water for all of us and for the various wildlife and their habitats also dependent on it.

2.0 LEGISLATION

2.1 THE WATER FRAMEWORK DIRECTIVE

In response to the increasing threat of pollution and the increasing demand from the public for cleaner rivers, lakes, beaches, the EU has developed the Water Framework Directive (WFD 60/2000/EC) [Ref 1]. This Directive is unique in that, for the first time, it establishes a framework for the protection of all waters including rivers and lakes, estuaries, coastal waters and groundwater, and their dependent wildlife/habitats under one piece of environmental legislation.

Specifically the WFD aims to:

- protect/enhance all waters, surface, ground and coastal waters
- achieve "good status" for all waters by December 2015
- manage water bodies based on river basins (or catchments)
- develop a "combined approach" for emission limit values and quality standards
- get the public involved
- streamline legislation.

2.2 IRISH WATER POLICY REGULATIONS

Ireland completed the first step in implementing the WFD in December 2003 by making the European Commission (Water Policy) Regulations, (S.I. No. 722 of 2003) [Ref 2] which transposed the WFD into Irish Law. The Water Policy Regulations appoint the Environmental Protection Agency (EPA) along with relevant Local Authorities and statutory organisations as the competent authorities for the Directive's implementation in Ireland.

The Irish legislation provides for the full implementation of the WFD including characterisation of each RBD, establishment of environmental objectives and the development of programmes of measures and river basin management plans (RBMP). It also provides for participation by interested parties, to facilitate this process Local Authorities are assigned responsibility for the co-ordination of actions by all relevant public authorities for water quality management within an RBD. The schedule for implementation of the WFD in Ireland is presented in Table 1.

Table 1 Implementation of the WFD as scheduled in Irish legislation (S.I. 722, 2003)

Key Date	*Key tasks*	
22nd December 2003	Implementation of the WFD on a National level	*Public Information and Consultation (ongoing)*
22nd June 2004	Establishing of River Basin Districts as the fundamental unit for applying and co-ordinating the Directive's provisions	
22nd December2004	Characterisation of River Basin Districts.	
22nd June 2006	Develop Classification systems for surface water and groundwater	
22nd June 2006	Establishing and maintaining appropriate Monitoring Programmes - Such monitoring must cover both surface and groundwater and must be operational by 22nd December 2006.	
22nd June 2006	Prepare and publish a work Programme and Timetable for the production of River Basin Management Plans (RBMP).	
22nd June 2007	Prepare and publish an overview of the significant water management issues identified in each river basin.	
22nd June 2008	Prepare and publish draft RBMPs and allow six months for written comment.	
22nd June 2008	Publish a draft Programmes of Measures for comment by any person for a six month period.	
22nd June 2009	Establish environmental objectives and final Programmes of Measures and developing RBMPs for their implementation	
22nd June 2009	Making of RBMPs	
2010	Water Pricing Policies that take into account the principle of 'cost recovery' for water services	
2012	Latest date for making operational the Programme of Measures	
2015	Meet environmental objectives of first RBMP and adopt the Second RBMP	

3.0 RIVER BASIN DISTRICTS

A key component of the WFD is the management of water resources based on catchments or river basin districts (RBDs). Ireland has taken the steps necessary under Article 3 of the WFD to divide the country into a series of RBDs. Eight RBDs have been established throughout the island of Ireland, North and South (Figure 1). The delineation of RBDs has been developed by Irish officials in consultation with the authorities in Northern Ireland (UK) and interested parties generally. The EU Commission has been provided with information on the competent authorities and a description of the geographical coverage of each RBD within Ireland.

The eight RBDs on the Island of Ireland include four basins located entirely within the South of Ireland (South Eastern, Eastern, Western and South Western) and three cross-border (international) basins (Shannon, North Western and Neagh-Bann). One further RBD is wholly internal to Northern Ireland (North Eastern).

4.0 IRISH ADMINISTRATIVE ARRANGEMENTS FOR WFD IMPLEMENTATION

4.1 NATIONAL COORDINATION GROUP (NCG)

The Department of Environment Heritage and Local Government (DEHLG) has established a group to co-ordinate and promote, at national level, implementation of the WFD. This structure is intended to streamline WFD implementation across all River Basin Districts in Ireland. The participants in the group include officials of relevant government departments, their related technical agencies and local authorities. These include:

- The River Basin District Coordinating Authorities
- Department of Environment, Heritage and Local Government
- Environmental Protection Agency
- Environment & Heritage Service, Northern Ireland
- Department of Communications, Marine and Natural Resources
- Marine Institute
- Geological Survey of Ireland
- Department of Agriculture and Food
- Central and Regional Fisheries Boards
- Office of Public Works
- Local Government Computer Services Board

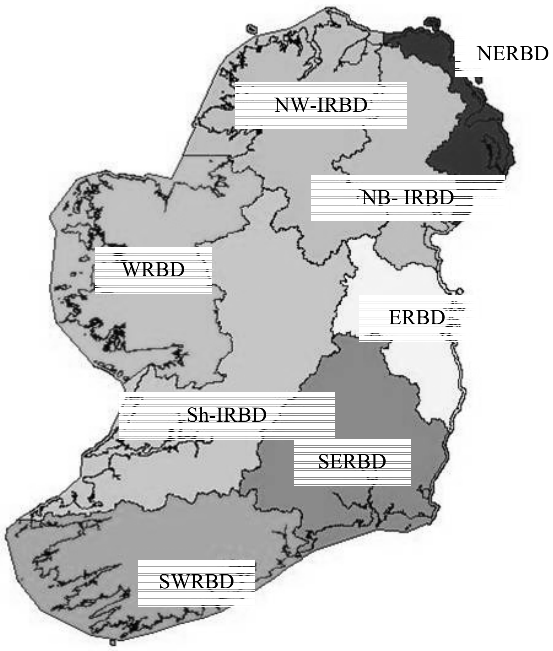

Figure 1 RBDs on the Island of Ireland

In addition to co-ordination at national level, officials of the DEHLG, other Government departments and their agencies are participating in technical groups and other initiatives to promote consistent and co-ordinated implementation of the WFD in the European Community, on a North/South basis and at a regional (RBD) level. The Irish authorities collaborate in the North-South Technical Advisory Group (NS-TAG) with the United Kingdom which shares the same land and marine eco-regions, and participating with other European Member States under various WFD initiatives such as the intercalibration exercise.

4.2 NATIONAL TECHNICAL COORDINATION GROUP (NTCG)

A National Technical Coordination Group (NTCG) has been established to provide specific guidance on the WFD in Ireland and to further ensure a coherent approach to its implementation. The Group is similar in structure to that of the NCG but comprises a larger working group which is focused on delivering the technical requirements of the Directive. It oversees the testing and application of

European technical guidance as well as ensuring co-ordination and consistency across Irish RBDs and with other Member States, the UK, Scotland and Northern Ireland in particular.

4.3 RIVER BASIN MANAGEMENT PROJECTS

The main activities for the implementation of the WFD in Ireland are taking place in the context of RBD Management Projects led by local authorities. The DEHLG has promoted the establishment of such projects to address all inland and coastal waters and has provided funding through the National Development Plan to Local Authorities to implement the projects. The projects are facilitating participation by all stakeholders, and will lead to the identification and implementation of effective measures for improved water management.

4.4 TECHNICAL SUB-GROUPS

Due to the scope and complexity of issues dealt with the NCG and NTCG establish technical sub-groups on a needs basis to address specific topics. These working groups draw on expertise from National Organisations and Public Bodies and from the consultants involved in RBD Projects.

5.0 RIVER BASIN DISTRICT PROJECTS

RBD Management Projects have been established in each RBD as the main vehicle for delivering the objectives of the WFD within Ireland. The projects will provide the basis for an integrated River Basin Management Plan that will be achieved by the following:

1. Collection and analysis of background information;
2. Characterisation of the RBD in accordance with the WFD;
3. Development of a river basin management system including;
    - a comprehensive water quality monitoring system for all waters within the RBD
    - a computerised (GIS) Management System
    - a programme of appropriate abatement measures
    - public awareness and consultation programme
    - an Environmental Management System (EMS)
4. Implementation of the River Basin Management System;
5. Preparation of a draft River Basin Management Plan.

The RBD Management Projects are 4 year projects funded by the DEHLG through the National Development Plan. Consultants have been appointed to develop the RBD Management System Projects and a project office has been established in each basin. The projects' implementation is supported by a Project Co-ordinator and a Project Steering Group and a Project Management (or Technical) Group have been established to direct and advise on the project's implementation.

6.0 ARTICLE 5 CHARACTERISATION REPORT

6.1 CHARACTERISATION

The WFD requires an Article 5 Characterisation report to be prepared for each RBD by December 2004. The key outputs of the characterisation process are:

- Identification of main pressures;
- Identification of water bodies at risk of failing to achieve at least good status by 2015;
- Identification of the need for further characterisation, including environmental monitoring, as a basis of planning the programme of measures;
- Establishment of the economic background for planning the programme of measures.

A national Characterisation Report was prepared for all Irish RBDs and the results reported to the EU commission in accordance with the WFD Article 5 deadline. The report represents a further important milestone for implementing the WFD in Ireland. This paper focuses on the findings of the pressures and impacts analysis. Details of the economic analysis are summarised in the Article 5 Characterisation Report.

The characterisation process involved extensive and detailed collaboration between a wide range of public authorities in collating a substantial body of existing datasets. The implementation of the WFD also entailed a series of specialist studies which required input from development studies and scientific research programmes. A significant number of new datasets have also been generated through commissioned work.

The Irish report provides an analysis of the characteristics of RBDs, undertakes a review of the impact of human activity on the status of waters and provides an economic analysis of water use. The report serves as a comprehensive assessment of all waters (groundwater, rivers, lakes, transition and coastal waters), establishes a baseline and identifies priority actions for subsequent stages in the river basin planning cycle.

6.2 WATERBODY DELINEATION & ANALYSIS OF TYPE

The first step in the characterisation process: waterbody delineation, requires that all natural waters are assigned to a category (e.g. river, lake, transitional, coastal or ground waters) and differentiated according to type which is dependant on physical attributes. All Irish waters have been grouped into types and further divided into individual management units called water bodies.

Waterbody delineation and typology studies were undertaken at a national level by organisations including the Environmental Protection Agency, Geological Survey of Ireland, Marine Institute with input from various academic groups and the RBD Projects.

The CIS Guidance on 'Identification of water bodies' (2003) [Ref 3] was used to develop an approach to delineating groundwater bodies in Ireland [Ref 4] applied in the following way:

- The aquifers were grouped into four groundwater body types, based on similarities in flow regime – karstic aquifers, gravel aquifers, productive fractured aquifers and poorly productive bedrock aquifers. The boundaries between adjacent groups usually represent either 'no flow' or 'relatively low flow' boundaries.
- As groundwater catchment divides or highs generally coincide with surface water catchment boundaries, surface water boundaries were used to complete groundwater body delineation.

For surface waters (rivers, lakes, transitional and coastal waters) water bodies are assigned to types that are ecologically meaningful.

All Irish rivers have been allocated to one of 12 primary types [Ref 5], which have been shown to be ecologically meaningful in unimpacted river systems. The river typology follows a WFD System B approach developed for Ireland which is primarily based on geology and its impact on water hardness and the slope or velocity of water in the channel. A wide range of potential characteristics were studied in order to assess their influence on the fauna and flora of Irish rivers (e.g. catchment size, altitude, latitude-longitude), but from a statistical point of view the most important controlling factors were geology/hardness and slope. In addition to the basic 12 types of river water bodies a number of special river water body types have been treated separately due to their rarity and unusual ecological nature.

A System B typology was found to be the most appropriate basis on which to define lake types in Ireland; 12 types have been identified using the factors; alkalinity (surrogate for geology), depth and size. Biological data from 60 high status lakes across several types and RBDs were used to test that the selected hydromorphological types, derived from these factors, can be discriminated on a biological basis [Ref 6]. Latitude and Longitude were not considered to be significant factors determining the flora and fauna of Irish lakes. A thirteenth type was identified to include a number of lakes at altitude >300m.

The typology for Transitional and Coastal Waters was developed on the basis of a SNIFFER research project "A proposed Typology for the UK and Republic of Ireland" [Ref 7]. The scheme is a System B approach which uses the obligatory factors of Latitude and Longitude, tidal range and salinity (common to both Transitional and Coastal Waters) along with the optional factors, for Transitional

Waters, mixing characteristics, mean substratum composition and extent of intertidal area and, for Coastal Waters, wave exposure. This scheme was considered to give the most ecologically relevant differentiation possible.

6.3 ANALYSIS OF HUMAN PRESSURES (RISK ASSESSMENT)

Following water body delineation, the next step in the characterisation process requires an analysis of the pressures and impacts that human activities exert on waters to be undertaken. The purpose of the analysis is to identify Irish surface water bodies and groundwater bodies at risk of failing the objectives of the directive due to the effect of human activities. The pressures and impacts analysis is also referred to as a risk analysis. The risk relates to the probability of a water body failing to achieve good status or suffering deterioration in status.

The pressures and impacts analysis is particularly important because it establishes a baseline for the river basin management planning cycle. It does this by identifying priorities for establishing programmes of mitigating measures where the risk is confirmed and/or monitoring strategies where further investigation is required to confirm the potential risk. The development of monitoring and management responses will be the focus of WFD implementation activities across Europe from early 2005 until the publication of River Basin Management Plans in 2009.

A sub group of the NTCG was established to develop Irish Risk Assessment methodologies for implementation by RBD Projects. The group adopted the following guiding principles with regard to the risk assessment process:

- The process and the results of the analysis should be transparent, comprehensible and all data and information should be made available to the public
- Risk analysis is not classification of status
- The results of the risk analysis will be used to help identify and prioritise the appropriate and iterative follow-up actions for the next stages of the planning process
- The analysis will ensure harmonised application of the key issues such as the baseline scenario and the identification of heavily modified water bodies
- Lack of relevant data should not be an excuse - demonstrate that you tried - make a “gap analysis”

Identification of all significant human pressures is the first stage in the assessment of human activities. Reporting Sheets developed by the European Commission specify the range and detail of the information that must be reported in the WFD Article 5 Characterisation Report. The WFD requires identification of groundwater water bodies “at risk” from quantitative pressures and qualitative pressures (i.e. point source and diffuse source pollution) in the Article 5 Report. Whilst surface waters must be assessed with regard to abstraction, morphological, point source, diffuse source and other pressures. Other pressures include such impacts as invasive or “alien” species and fishing pressures.

A risk assessment scoping study was undertaken to identify the key pressures on Irish water bodies and establish which would require a GIS based Risk Assessment approach. Identified issues included nutrient and organic pollution of all waters, abstraction from inland waters and acidification of inland surface waters.

The second stage in the assessment of human activities is the application of the risk assessment procedures to groundwaters and surface waters to identify the relative significance of pressures. Ireland has consulted and, where appropriate, adapted the risk assessment methodologies prepared by the UK TAG, again to aid transparency and consistency in the analysis throughout the ecoregion.

Risk assessment methods have been developed and applied to all water categories (groundwaters, rivers, lakes, transitional and coastal waters).

The Irish groundwater assessments (Figure 2) use a simple pressure, pathway, receptor model to identify where the impacts on groundwaters are likely to occur, as presented in “The Approach to

Groundwater Risk Assessment" [Ref 8]. The risk assessment procedure for groundwaters addresses abstraction, saline intrusion, diffuse and point pressures [Ref 9-11]. The groundwater methods of assessment are generally more predictive than those applied to surface waters partly due to the limited availability of impact data for groundwater. Impact data has been used to verify the individual groundwater assessments to ensure that the models adopted are robust and to refine the final risk category of water bodies where good impact data are available.

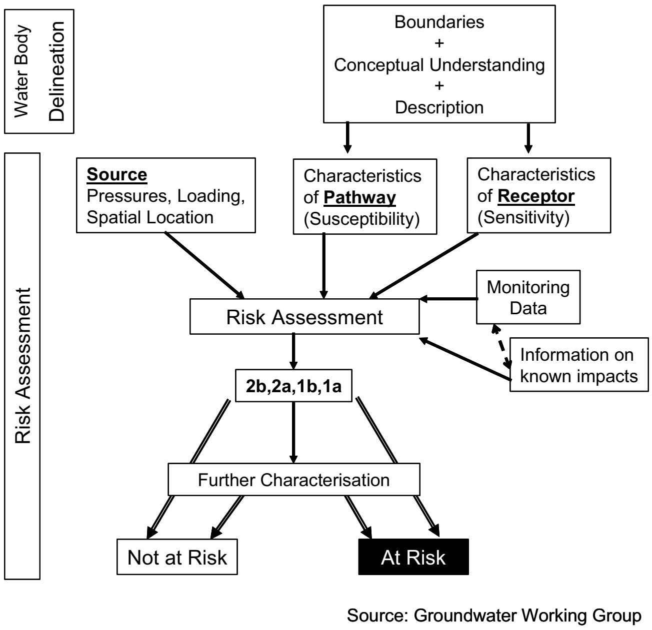

Figure 2 Groundwater Pressure Pathway Receptor Model

The surface waters risk assessment procedure includes abstraction, flow regulation, morphological, point and diffuse pressure assessments [Ref 12-20]. The surface water analysis also incorporates impact data from national river, lake and marine monitoring datasets. The surface water procedures included investigation of additional risk factors such as the effects of fishery activities and the presence of introduced invasive (or alien) aquatic species which might jeopardise the survival of native species. Compliance with the standards set in other directives to protect the environment was also considered in the surface water risk assessment process.

The risk assessment presented in the Irish Characterisation Report relates to current pressures and does not attempt to predict the effect of any future changes in human activities. The implications of future changes in pressures and the management of these activities looking forward to 2015 will be considered as part of a further characterisation process and will be incorporated into the draft River Basin Management Plans in 2008.

7.0 CONCLUSIONS

The implementation of WFD has presented EU Member States with a number of technical challenges, particularly the preparation of the Article 5 Characterisation Report. Ireland has made significant progress through the establishment of the river basin district projects which collaborated with state organisations to produce the Characterisation Report.

The next phase of the RBMP cycle will focus on the further characterisation of water bodies at risk to improve the information available and to increase the confidence in the risk assessments. Details of the planned actions to address these data gaps and uncertainties during the next planning phase (2005-2008) are provided in the national Article 5 Characterisation Report.

Achieving good status for all waters by 2015 will be a considerable challenge. Significant effort and resources will be required to ensure sustainable water management is implemented on schedule as required by the WFD. The completion of the initial characterisation and analysis provides the baseline necessary to begin the next phase of the process of river basin management.

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THE CHARACTERISATION AND ANALYSIS OF IRELAND'S RIVER BASIN DISTRICTS: GROUNDWATER ASPECTS

Donal Daly, Geological Survey of Ireland and Convenor of WFD Groundwater Working Group[4]

ABSTRACT

Progress is always pleasing to report. In the last three years, the implementation of the Water Framework Directive (WFD) and the work undertaken by the GSI, Teagasc, EPA and RBD (river basin district) consultants have advanced considerably the role and understanding of groundwater in Ireland. Groundwater has been 'characterised' and, in the process, a new aquifer map of Ireland has been produced, all readily available groundwater data have been collected, soils and subsoils mapping have been undertaken, the hydrochemistry of our groundwater has been assessed and over 700 'groundwater bodies' (the management units of the WFD) have been delineated and described.

Generally, groundwater is a 'hidden resource', and the focus in the past has been mainly concerned with its use for drinking water. Now the focus is broader, and the WFD requires that it also be seen in terms of the link with, and contribution to, ecosystems, whether in surface water or wetlands. Risk characterisation, which integrates pressures and impacts with the physical characterisation, has been undertaken to evaluate whether the groundwater bodies are 'at risk' of failing to meet the environmental objectives of the WFD. This has shown that a high proportion of the groundwater bodies(61%) , comprising 27% of the country, are indeed 'at significant risk' or 'probably at significant risk', either from diffuse sources of pollution (mainly agricultural) or point sources (mainly old landfills, urban areas, or contaminated land).

Testing challenges are ahead. The first stage of implementation, completed in March 2005, was a screening exercise, pointing the way forward and highlighting the main issues for the future. Now further characterisation and monitoring will be undertaken to reduce uncertainties and check the validity of the risk assessment results. In the process, our understanding of groundwater in Ireland will improve further. More controversially perhaps, a programme of measures will be required to ensure that the status of groundwater bodies classed as 'good' does not deteriorate, and that the status of those classed as 'poor' is restored to 'good'. This is likely to have implications for some current land uses in Ireland

1. INTRODUCTION

Since 2001, work undertaken by the Geological Survey of Ireland (GSI) and River Basin District (RBD) consultants, as part of implementation of the WFD, has advanced substantially the understanding and mapping of Ireland's groundwater. The work was 'overseen' by the WFD Groundwater Working Group (WG) and the WFD Technical Co-ordination Working Group. This paper is given on behalf of the Groundwater WG and is based largely on the WFD National Characterisation Report, which is available on the www.wfdireland.ie website.

The groundwater characterisation process involves two elements: physical characterisation and risk characterisation. This paper summarises the work undertaken and the results for each element.

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2. PHYSICAL CHARACTERISATION

2.1 SUMMARY OF WORK UNDERTAKEN

Physical characterisation provides relevant information and maps to enable:

- ♦ groundwater bodies to be delineated and described, and
- ♦ the risk assessment process to be undertaken by providing the location and description of the receptors and the geological pathways that link pressures and receptors.

The physical characterisation process required collection of new data, mapping, compilation and assessment of existing and new data, and production of relevant maps and reports. The work undertaken was as follows:

1. Production of a national digital bedrock geology map (by GSI);
2. Grouping of rock units on the basis of similarities in both lithology and likely hydrogeological properties (GSI);
3. Production of national maps of soils and subsoils (by Teagasc);
4. Collection and compilation of hydrogeological and depth to bedrock data (GSI);
5. Assessment of the hydrogeological properties of each rock unit, using lithogical, structural and hydrogeological information (GSI);
6. Production of a national map of bedrock and sand/gravel aquifers, giving a total of eight aquifer categories, based on resource value and hydrogeological properties (GSI);
7. Compilation of a groundwater vulnerability map for the proportion of the country (~50%) for which existing county vulnerability maps were available; as well as preparation of a map of 'extreme' vulnerability (<3m soil/subsoil) areas for the remainder of the country (GSI & RBD consultants).
8. Delineation of groundwater bodies (GSI).

2.2 LOCATION AND BOUNDARIES OF THE GROUNDWATER BODIES

The EU WFD CIS Guidance on 'Identification of water bodies' (2003) was applied in the following way:

- ♦ Aquifers were grouped into four groundwater body types, based on similarities in flow regime – karstic aquifers, gravel aquifers, productive fractured aquifers and poorly productive bedrock aquifers. The boundaries between adjacent groups usually represent either 'no flow' or 'relatively low flow' boundaries.
- ♦ As groundwater catchment divides or highs generally coincide with surface water catchment boundaries, Hydrometric Area boundaries were used to complete groundwater body delineation.
- ♦ A total of 383 groundwater bodies5 (GWBs) were delineated using these principles.
- ♦ Where point pollution sources or the predicted impact on groundwater dependent ecosystems placed areas within these groundwater bodies 'at risk', new groundwater bodies were delineated using hydrogeological boundaries, giving a total of 757 groundwater bodies. The number and type of groundwater bodies is summarised in Table 1.

Table 1 Summary of groundwater bodies based on flow regimes

Groundwater body types based on flow regime	Number of groundwater bodies	% of number	% area of country
Karstic	202	26.7	19.6
Productive fissured bedrock	109	14.4	7.4
Gravel	70	9.2	2
Poorly productive bedrock	376	49.7	71

[5] The 'groundwater body' is the management unit for the WFD.

2.3 DESCRIPTION OF GROUNDWATER BODIES

Based on the requirements of the Directive and the compiled data and maps, a descriptive table – Table 2 – summarising the relevant physical characteristics was prepared. This table has been completed for each of the groundwater bodies.

In general, Ireland has a diverse, complex bedrock and subsoil geology. Consequently, the groundwater flow regime varies from intergranular flow in subsoils to fissure flow in bedrock and karstic (conduit) flow in pure limestones. This influences not only groundwater abstraction, but also pollutant movement and attenuation, and interaction with surface water. The characteristics of the groundwater bodies are summarised below, subdividing them on the basis of groundwater flow regime.

Karstified GWBs: generally distinctive karst landforms; drainage largely underground in solutionally-enlarged fissures (joints, fractures, bedding planes); variable to high transmissivity; high groundwater velocity; low effective porosity; high degree of interconnection between groundwater and surface water, with sinking streams and large springs; streams often flashy and may be dry in summer; baseflow variable; groundwater level and stream flow hydrographs usually peaky; drainage density low; potentially long groundwater flow paths.

Productive Fissured Bedrock GWBs: groundwater flow in fissures (joints, fractures, bedding planes); moderate to high transmissivity; low effective porosity; contribute baseflow to streams and maintain dry weather flows; occasional large springs may occur; potentially long groundwater flow paths; confined in places.

Gravel GWBs: intergranular flow; high permeability; high effective porosity; tend to be relatively small in area; occasional large springs; contribute substantially to stream baseflow; low drainage density; potentially long flow paths.

Poorly Productive Bedrock GWBs: groundwater flow in fissures; most flow is at shallow depth in the weathered layer at the top of the bedrock; significant flows can occur in widely dispersed deeper fracture zones; low transmissivity; high groundwater gradients; low baseflow contribution to streams; high drainage density; generally short underground flow paths.

Table 2 Initial Characterisation – Descriptions of Groundwater Bodies

Hydrometric Area **Local Authority**		**Associated surface water bodies**	**Associated terrestrial ecosystems**	**Area (km2)**
Topography				
Geology and Aquifers	Aquifer type(s) Main aquifer lithologies			
	Key structures.			
	Key properties			
	Thickness			
Overlying Strata	Lithologies			
	Thickness			
	% area aquifer near surface			
	Vulnerability			
Recharge	Main recharge mechanisms			
	Est. recharge rates			
Discharge	Springs and large known abstractions			
	Main discharge mechanisms			
	Hydrochemical Signature			
Groundwater Flow Paths				
Groundwater & surface water interactions				
Conceptual model				
Attachments				
Instrumentation	Stream gauge: Borehole Hydrograph: EPA Representative Monitoring boreholes:			
Information Sources				

As a result of the work undertaken, virtually for the first time in the Republic of Ireland, it is possible to characterise, at both a regional and local scale, all of the country in a way that enables water flow, particularly groundwater flow, and contaminant movement to be understood and described. Conceptual models, providing a relatively simple 3-D understanding of water flow, are now available for all of the land surface.

2.4 GENERAL CHARACTER OF SUBSOILS OVERLYING GROUNDWATER

More than 90% of the RBDs are covered by subsoils. These provide the protecting, filtering layer over groundwater and also influence recharge. However, they are highly variable in distribution, composition, permeability and thickness. The main subsoil types and the proportion of the land surface covered by each type is as follows (information provided by Robbie Meehan, Spatial Analysis Group, Teagasc): glacial till (62.5%), sand/gravel (4.3%), alluvial sediments (0.6%), lacustrine silts and clays (0.4%), beach/wind blown sediments (0.2%), peat (18.9%) and made ground (1.2%). The remainder of the land surface (11.9%) consists of outcrop/subcrop.

Subsoil permeability maps, subdividing the subsoils into three categories – high, moderate and low – were available for ~40% of the country from GSI. For the remainder of the country subsoil permeability has been estimated, although with a considerable level of uncertainty.

Soil maps were produced by Teagasc, subdividing soils into ‘wet’ or ‘dry’, and ‘acid’ or ‘basic’. While the areas of ‘wet’ soils are underestimated in places, these maps provide an essential component of the physical characterisation and risk assessment.

In karstified GWBs, bypassing of the overlying protecting layers may occur at karst features, such as swallow holes. Compilation and some mapping of these features has been undertaken.

Vulnerability maps were available for 50% of the country from GSI. For the remainder, the ‘extremely’ vulnerable areas (i.e. areas with <3 m soil and subsoil above bedrock) were mapped by RBD consultants, as pressures in these areas pose the greatest threat to groundwater. The proportions of the country with ‘extremely’ vulnerable groundwater are given in Table 3.

Table 3 Summary information on proportion of country with ‘extremely’ vulnerable groundwater

Groundwater body types based on flow regime	**Area mapped as ‘extremely’ vulnerable**		**% total area mapped as ‘extremely’ vulnerable**	**% area of each GWB type mapped as ‘extremely’ vulnerable**	**% area below 200 m mapped as ‘extremely’ vulnerable**
	Total (km^2)	**Below 200 m contour**			
Karstic	3175	2991	4.6	23	-
Productive fissured bedrock	1217	1068	1.8	24	-
Sand/gravel	43	43	0.1	3	-
Poorly productive bedrock	19701	12926	28.5	40	-
All types	24136	17228	35	-	29

2.5 GROUNDWATER DEPENDENT TERRESTRIAL ECOSYSTEMS (GWDTEs)

The achievement of “good status” for groundwater is dependent on ensuring appropriate groundwater conditions for the maintenance of “good status” for surface waters and the avoidance of significant damage to groundwater dependant terrestrial ecosystems (GWDTEs). Groundwater dependent ecosystems cover a wide range of types including surface water bodies such as lakes, rivers and lagoons, and wetlands such as turloughs, fens, wet woodlands and bogs. In relation to GWDTEs, only those of European importance, i.e. in SACs or SPAs on the Register of Protected Areas, were assessed.

3 RISK CHARACTERISATION

3.1 ROLE OF THE RISK CONCEPT

Risk assessment is at the heart of effective river basin planning and therefore of the WFD. In implementing the WFD, risk assessment allows environmental problems to be identified, monitoring programmes to be designed, and appropriate, cost effective protection and improvement measures to be formulated and implemented. The basic unit of risk assessment is the 'groundwater body', which is defined in the Directive as 'a distinct volume of groundwater within an aquifer or aquifers'. The process follows the pressure-pathway-receptor approach. The output of the risk assessment is a list of water bodies, including groundwater bodies, considered to be 'at risk' of failing to meet the environmental objectives of the Directive. In Ireland, four risk categories, designated as **2b, 2a, 1b and 1a** (see Table 4)**,** are defined for the purpose of focussing actions during the next phase (2005-2008).

Table 4 Irish Risk Assessment Reporting Categories

WFD Risk Category	Irish Reporting Risk Categories
Water bodies **at risk** of failing to achieve an environmental objective	**(1a) Water bodies at significant risk** **Action:** Identifies water bodies for which consideration of appropriate measures to improve status can start as soon as practical
	(1b) Water bodies probably at significant risk but for which further information will be needed to confirm that this view is correct **Action:** Focus for more detailed risk assessments (including, where necessary, further characterisation) aimed at determining whether or not the water bodies in this category are at significant risk in time for the publication of the interim overview of significant water management issues in 2007
Water bodies **not at risk** of failing to achieve an environmental objective	**(2a) Water bodies probably not at significant risk** on the basis of available information for which confidence in the available information being comprehensive and reliable is lower **Action:** Focus for more detailed risk assessments aimed at determining whether or not the water bodies in this category are not at significant risk in time for the publication of the draft River Basin Management Plan due to be completed in 2008
	(2b) Water bodies not at significant risk on the basis of available information for which confidence in the available information being comprehensive and reliable is high **Action:** Identifies water bodies for which consideration of appropriate measures to ensure no deterioration in status can start as soon as practical

The focus of the risk assessment approach for the WFD has broadened; whereas in the past the receptors of concern were groundwater resources and drinking water abstraction points, now groundwater dependent river and lakes, and groundwater dependent terrestrial ecosystems must also be taken into account (see Figure 4).

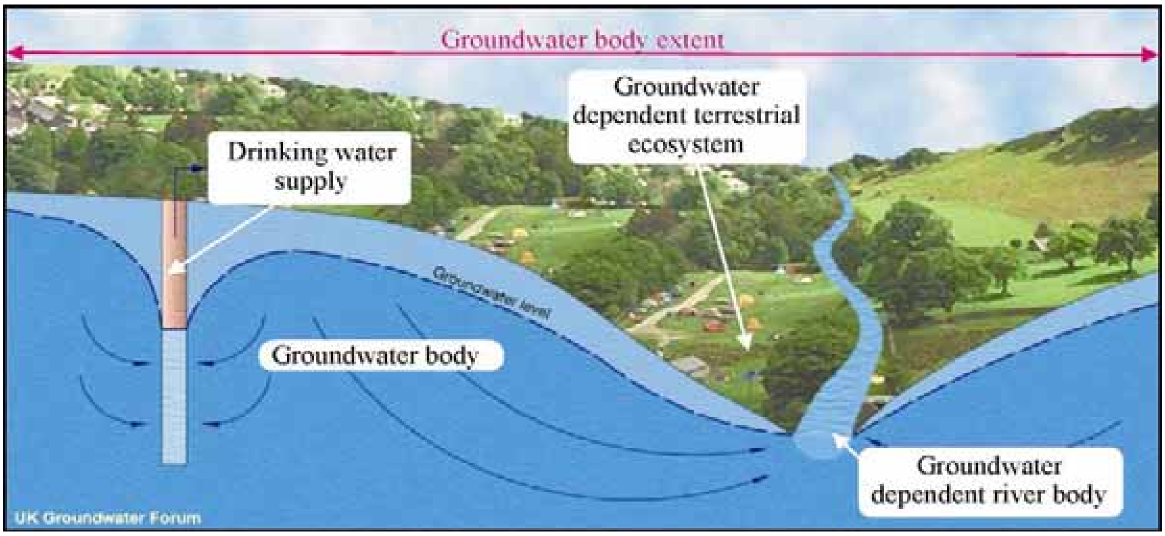

Figure 4: Diagrammatic illustration of a groundwater body showing the range of receptors that must be considered

3.2 SUMMARY OF RISK ASSESSMENT PROCESS

The relevant factors involved in the risk assessment are outlined below.

Pressure Magnitude (Source) Factors

- ♦ Identification of pressures.
- ♦ Estimation of pollutant loading (quantity and concentration) for main pollutant types (e.g. mobile inorganic (NO_3) and less mobile inorganic (PO_4) constituents).
- ♦ Development of threshold values for particular pressure magnitudes and pollutant types, in the form of matrices (e.g. more than a certain number of livestock units/ha could be categorised as a high pressure magnitude for both NO_3 and PO_4).
- ♦ For certain pollutants (e.g. trace organics), the presence or absence of a source is the determining factor.

Pathway (both over ground and underground) Factors

- ♦ Compilation and characterisation of relevant elements, such as soils, subsoils, aquifers, vulnerability.
- ♦ Classification of pathway information as 'pathway susceptibility' for the main pollutant types (mobile inorganic substances, such as nitrate; less mobile inorganic substances, such as phosphate; mobile organic substances, such as pesticides and hydrocarbons; less mobile organic substances) into 4 categories, ranging from 'extremely high' to 'low'.

Receptor Factors

- ♦ Evaluation of the sensitivity of different receptors to pressures (pollutants and/or abstraction) and categorisation into high and moderate sensitivity, e.g. fens are more sensitive than raised bogs to groundwater abstraction but are less sensitive to nutrients.

Integrating Source, Pathway and Receptor Factors

- ♦ This integration enables the predicted Risk Assessment category to be determined.

Impact Data

- ♦ Where adequate representative impact data are available, the predicted risk category can be adjusted. However, data cannot be used to adjust the category downwards (i.e. to a lower risk category).

The general process is illustrated by the matrices below.

A. Pathway susceptibility

PATHWAY SUSCEPTIBILITY			Flow Regime (Horizontal pathway)			
			Karst aquifers	*Fissured aquifers*	*Intergranular aquifers*	*Poorly productive aquifers*
Vertical pathway***	Soil & subsoil	'Wet' soil				
		Subsoil permeability				
	Vulnerability	Extreme				
		High				
		Moderate				
		Low				
		High to Low**				

Extreme, High, Moderate or Low

B. Impact potential

IMPACT POTENTIAL		Pathway Susceptibility (from Table A)			
		Extreme	*High*	*Moderate*	*Low*
Pressure magnitude					

High, Moderate, Low or Negligible

C. Risk category based on predictive risk assessment

RISK CATEGORY		Proportion of assessment area with high and moderate impact potential					
		>40%	25-40%	15-25%	10-15%	5-10%	<5%
Receptor Sensitivity	High		1a, 1b, 2a or 2b (see Table 4)				
	Moderate						

D. Risk category of groundwater body adjusted using available impact data

Predictive risk category	Adjustments made using available groundwater impact data	
	Data criteria	*Adjusted risk category*
1a, 1b, 2a or 2b	Usually these are threshold values	1a or 1b, depending on level of confidence in the monitoring data. 2a or 2b

3.3 UNDERTAKING THE RISK ASSESSMENT

The risk assessment methodology is based on considering four receptors – groundwater bodies, groundwater dependent rivers and lakes, groundwater dependent terrestrial ecosystems, and drinking water abstraction points. The environmental objectives, pathway susceptibility and sensitivity of the receptors frequently vary. Therefore, for each of these receptors, the impact of three pressure types – groundwater abstraction, diffuse source pollutants and point source pollutants – is considered separately. Risk assessments methodologies were developed by the Groundwater WG for each scenario listed in Table 5 (see Groundwater Guidance document GW8 for details), and 19 risk assessments were undertaken by the RBD consultants.

Table 5 WFD Groundwater Risk Assessment Sheets for Relevant Receptors and Pressures

RECEPTOR	Groundwater Body	Groundwater dependent rivers, lakes & estuaries	GWDTEs	Abstraction points
WFD OBJECTIVE PRESSURE	Status, trends	Status	Status	Drinking water protected areas
Groundwater Abstraction				
Water balance	GWB1	SW1	GWDTE1	-
Intrusion	GWB2	-	-	-
Diffuse Source Pollutants				
Mobile nutrients (e.g. NO_3)	GWB3	SW2		DWPA1
Less mobile nutrients (e.g. PO_4)	-	SW3	GWDTE2a & 2b	-
Mobile chemicals	GWB4	SW4		DWPA2
Clustered on-site systems & leaking urban sewerage systems	GWB5	SW5	GWDTE3	
Sheep dip	D	D	D	D
Less mobile chemicals	-	-	-	-
Microbial organisms	-	-	-	D
Point Source Pollutants				
Mining	GWB6	SW6	GWDTE4	
Quarries	GWB7		GWDTE5	
Landfills	GWB8		GWDTE6	
Oil industry infrastructure	GWB9		GWDTE7	
Contaminated land	GWB10		GWDTE8	
Trade effluent discharges	GWB11			
Urban wastewater discharges	GWB12		GWDTE9	

Notes:

1. Heavy borders indicate identical matrices for one or more risk assessment sheet.
2. "D": assessment planned but deferred until data become available.
3. "-": No assessment planned.

The risk assessment process is a screening exercise, using readily available geoscientific and pressure layers in a GIS, with a completion date of March 2005. The results will be checked and refined during the next phase of the implementation of the WFD.

4. SUMMARY OF RISK ASSESSMENT RESULTS

4.1 GROUNDWATER ABSTRACTION PRESSURES

The results, which are taken from the National Characterisation Report, are summarised in Table 6.

Table 6 Groundwater bodies affected by abstractions and saline intrusion

Reporting category	Number of GWBs	% of number	% area of country
1a	6	0.8	0.2
1b	36	4.8	0.9
2a	76	10.0	13.1
2b	639	84.4	85.8
1a+1b	42	5.6	1.1

4.2 DIFFUSE SOURCE POLLUTANT PRESSURES

The results are summarised in Table 7.

Table 7 Groundwater bodies affected by diffuse source pollution

Reporting category	No. of GWBs	% of number	% area of country
1a	0	0	0
1b	281	37.1	24.6
2a	199	26.3	37.1
2b	277	36.6	38.3
1a+1b	279	37.1	24.6

4.3 POINT SOURCE POLLUTANT PRESSURES

The results are summarised in Table 8.

Table 8 Groundwater bodies affected by point source pollution

Reporting category	No. of GWBs	% of number	% area of country
1a	33	4.3	1.6
1b	262	34.6	1.9
2a	78	10.3	22.7
2b	384	50.7	73.8
1a+1b	295	39.0	3.5

4.4 OVERALL SUMMARY

The overall results are summarised in Table 9.

Table 9 Summary of groundwater bodies affected by all pressures

Reporting category	No. of GWBs	% of number	% area of country
1a	39	5.1	1.8
1b	420	55.5	24.9
2a	174	23.0	43.4
2b	124	16.4	25.5
1a+1b	459	60.6	26.7

5. GUIDANCE DOCUMENTS

Eleven guidance documents, which are available on the www.wfdireland.ie website, were prepared by the Groundwater WG. They are listed in Table 10.

Table 10 List of groundwater guidance documents

Number	Date	Full Title
GW1	2001	Technical Requirements for Groundwater and Related Aspects
GW2	2003	Approach to Delineation of Groundwater Bodies
GW3	2004	The Calcareous/Non-Calcareous ("Siliceous") Classification of Bedrock Aquifers in the Republic Of Ireland
GW4	2003	Guidance on Pressures and Impacts Methodology
GW5	2004	Guidance on the Assessment of the Impact of Groundwater Abstractions
GW6	2004	Advice on the Implementation of Guidance on Monitoring Groundwater
GW7	2004	Point Source Pressure Risk Assessment for Groundwaters
GW8	2004	Methodology for Risk Characterisation of Ireland's Groundwater
GW9	2005	Guidance on the Assessment of Pressures and Impacts on Groundwater Dependent Terrestrial Ecosystems Risk Assessment Sheet GWDTE 2a – Turloughs
GW10	2005	Verifying the Predictive Risk Assessment Methodology for Mobile Diffuse Inorganic Pollutants (NO_3)
GW11	2005	Guidance on the Application of Groundwater Risk Assessment Sheets SW 1-6 and GWDTE 1-9 to Areas Designated for the Protection of Habitats and Species

6. LESS STRINGENT OBJECTIVES

For groundwater bodies so affected by human activities that it may be unfeasible or unreasonably expensive to achieve good status, less stringent objectives (LSOs) may be applied to. This essentially means a derogation from the requirements of the WFD. However, the choice of these GWBs must be justified by 2008. In total, 35 candidate LSOs have been chosen: 19 in the vicinity of mines; 11 due to contaminated land problems; and 5 urban areas – Dublin, Cork, Limerick, Galway and Waterford.

7. DISCUSSION & CONCLUSIONS

7.1 PHYSICAL CHARACTERISATION

Data collection and assessment, production of new maps in a GIS and description of the groundwater flow regime for the total land surface (by means of GSI reports on 383 groundwater bodies) have increased significantly the availability of useful information on groundwater. For instance, a bedrock geology map, oriented to hydrogeological characteristics, and an aquifer map can now be viewed, free of charge, on the GSI website - www.gsi.ie. Subsoils maps are available for a substantial proportion of the country and country-wide subsoil mapping will be completed by Teagasc in early 2006.

7.2 RISK CHARACTERISATION

Diffuse source pollution has been shown to pose a significant risk to groundwater in ~25% of the country. Nitrate from agricultural activities poses the main threat to groundwater in the south-east and south, while phosphate from agricultural activities entering groundwater poses a threat to surface water and terrestrial ecosystems in the karst areas of the west. Points sources of pollution (old dumps, urban areas, mines, etc) are considered to be putting localised areas at risk. Unlike most other European countries, groundwater abstraction is not considered to be a major threat, except possibly in a very few areas.

7.3 VALUE OF GUIDANCE DOCUMENTS

The production of the guidance documents, which involved input from a wide range of specialists, has increased and broadened our understanding of groundwater in Ireland, and provides a good basis and signpost for future work. For example:

- ♦ GW3 required an assessment of the hydrochemistry of our aquifers, resulting in a subdivision of all bedrock units into calcareous and siliceous categories.
- ♦ GW5 provides a unified approach to estimation of recharge for any part of the country.
- ♦ GW8, which was developed in association with the Scottish Environmental Protection Agency, outlines a national, physically-based approach to considering risk to groundwater and enabling the higher risk areas to be delineated. In particular, it provides a consistent approach to assessing risk.
- ♦ GW9 and GW11, which were developed in association with ecologists, are a good starting point for considering risk to ecosystems; a critical element of the WFD, but for many hydrogeologists a new area.
- ♦ GW10, while needing more development and checking, provides a means of predicting regional nitrate and phosphate concentrations in groundwater.

8. FUTURE CHALLENGES

Characterisation is but the first stage in the implementation of the WFD. Further characterisation of groundwater bodies considered to be 'at risk' must now commence to deal with uncertainties arising from the characterisation process and to confirm the risk categories.

Monitoring programmes must be established by the end of 2006, with the aim of:
- assisting groundwater body characterisation;
- assisting and validating risk assessments as part of characterisation;
- helping to establish the groundwater status of groundwater bodies or groups of bodies;
- checking for trends; and
- checking the effectiveness of the programme of measures designed to achieve the environmental objectives of the WFD.

The means of achieving the environmental objectives of the WFD is through a programme of measures, which will take account of the characterisation and monitoring results. This will present a significant challenge in the future as it is likely to have implications for current land use practices.

9. ACKNOWLEDGEMENTS

This paper is based largely on the groundwater-oriented sections in the WFD National Characterisation Report and is given on behalf of the Groundwater WG.

The paper is published with the permission of Dr. Peadar McArdle, Director, Geological Survey of Ireland.

GROUNDWATER MONITORING FOR IMPLEMENTATION OF THE WATER FRAMEWORK DIRECTIVE
INITIAL RESULTS AND ASSESSMENT

Sean Moran, Senior Hydrogeologist - O'Callaghan Moran & Associates
Gerry Baker, Hydrogeologist - O'Callaghan Moran & Associates

ABSTRACT

Monitoring of groundwater chemical and quantitative status is a primary requirement for the implementation of the Water Framework Directive 2000/60/EC. Existing chemical and quantitative data was used in the Initial Characterisation process recently completed for each of the seven Irish river basin districts to assess and refine risk assessments. Groundwater Monitoring Programmes must be established in each River Basin District by June 2006. The Monitoring Programmes will be used to a) assess impacts in those groundwater bodies deemed to be at risk of failing to achieve good status, b) to confirm good status in those groundwater bodies where good status already exists and c) to establish trends/improvement in water quality following the implementation of measures in those groundwater bodies where such actions are deemed necessary to improve chemical and/or quantitative status. This paper presents an assessment of how the existing groundwater monitoring networks used by local authorities and the Environmental Protection Agency were screened and validated for inclusion in the Initial Characterisation process in the South East River Basin District (SERBD). It describes the Monitoring Programme established in the SERBD, which is being used to assess the range and frequency of parameters likely to be required in future groundwater monitoring programmes, presents some of the findings of the Monitoring Programme and briefly outlines the way forward for groundwater monitoring as part of the implementation of the Water Framework Directive in Ireland.

1.0 ASSESSMENT OF THE EXISTING GROUNDWATER MONITORING NETWORK IN THE SOUTH EASTERN RIVER BASIN DISTRICT

As part of the initial characterisation process in the SERBD the project team completed a comprehensive review of all the available groundwater quality monitoring data in the SERBD. The initial desk study review included data maintained by the Environmental Protection Agency (EPA) as part of the national groundwater monitoring programme, data maintained by the 13 local authorities in the SERBD, data from the Geological Survey of Ireland (GSI) compiled as Source Protection Reports and Groundwater Protection Schemes, data from private groundwater group schemes and industries using groundwater supply. Further information was obtained from a previous screening programme undertaken as part of EU STRIDE funded programme by Mr. Jer Keohane on behalf of the Regional Water Laboratory, Kilkenny 1994.

This review identified an initial list of 171 existing qualitative groundwater monitoring points from which information was gathered to assist in the establishment of groundwater chemical status and 69 level monitoring points used in quantitative status assessment. To assess how representative the data was O'Callaghan Moran & Associates (OCM) developed a screening programme incorporating a conceptual model of groundwater flow by combining information on the surrounding topography, geology, hydrology and hydrogeology. Conceptual models of the Groundwater Bodies (GWB) in which the monitoring points are located were completed by the GSI and are being used to improve the assessment process for the development of the groundwater monitoring networks nationally.

The screening programme also involved the compilation of information on the construction details of the monitoring points. A screening log was developed for monitoring points used for abstraction and separately those points used to establish groundwater level. The screening logs were subsequently reviewed and improved by a subcommittee of the Groundwater Working Group (GWG), the national expert panel assigned responsibility for providing guidance for implementation of the WFD in Ireland, established in 2002. The GWG prepared a guidance document, *Advice on the Implementation of Guidance on Monitoring Groundwater* in 2004. The screening logs are included as an Appendix to the guidance document.

The screening logs were used to obtain relevant information on construction details including information on level of well head protection, abstraction rates, and extent of monitoring and observation of practices in the local area. The information was collected by the SERBD Monitoring Team under the supervision of OCM.

Following completion of the screening programme 117 of the 177 monitoring points were considered to be suitable for use in the initial characterisation programme (Figure 1). The main reasons for elimination of monitoring points were low rates of abstraction, which would indicate that a monitoring point was not representative of a large enough portion of the GWB, poor well head protection, supplies were part surface part groundwater, were too shallow or straddled formations. Typically three monitoring points were selected per GWB. In the larger GWBs a larger number of monitoring points were included where these were available.

There are at present 69 known locations where the EPA or GSI have monitored groundwater level within the SERBD. The EPA has monitored 40 of these sites, the remaining 29 are or were used by the GSI. Many of these locations are still in use by the EPA and GSI. A small number of the GSI boreholes are fitted with automatic level recorders. Some of these monitoring points have records dating to the 1970s. The review of the level monitoring points is still ongoing.

The quantitative risk assessment process and level monitoring indicates that abstraction(dewatering) of groundwater at Lisheen and Galmoy mines is affecting quantitative status in these groundwater bodies. There is also potential for abstraction risk from over abstraction and possibly saline intrusion in the Fardystown Groundwater Body in Co. Wexford. Because 30% of the existing monitoring points are considered unsuitable for use as a result of screening there will be a need to install new monitoring points to support the monitoring programmes required under the Directive. The number of additional points required is currently under review.

The review of the existing groundwater quality monitoring data (primarily local authorities and EPA) indicated that the data sets were limited in terms of the range of parameters analysed and the frequency of analysis undertaken. It was therefore proposed to establish a preliminary groundwater monitoring programme in the SERBD for a 12 month period commencing in April 2004. The purpose was to determine the most effective parameter range and frequency to establish chemical status of groundwater bodies as part of the surveillance and operational monitoring programmes.

The parameters of water quality assessed were the Core list of parameters developed by the Environmental Protection Agency (EPA) and were used to establish general groundwater quality as presented in the EPA publication Towards Setting Guideline Values for the Protection of Groundwater in Ireland 2003.

Monitoring of groundwater chemical status has been undertaken for 17 of the 35 EPA Core list of groundwater quality indicator parameters on the 117 points on a monthly basis for one year. The selected parameters are ones that can be analysed at the SERBD Laboratory in Kilkenny. Because of the potential cost associated with sampling all 35 Core list parameters in all 117 points on a monthly basis for one year a sub-group of 14 sampling points were identified where the full 35 Core list parameters is also being tested in selected GWBs. (These points represent varied hydrogeological conditions primarily Regionally Important, Karst, Fractured and Sand and Gravel aquifers).

It is intended that the programme will provide guidance on a national level in terms of the range and frequency of monitoring required to characterise the chemical status of groundwater bodies.

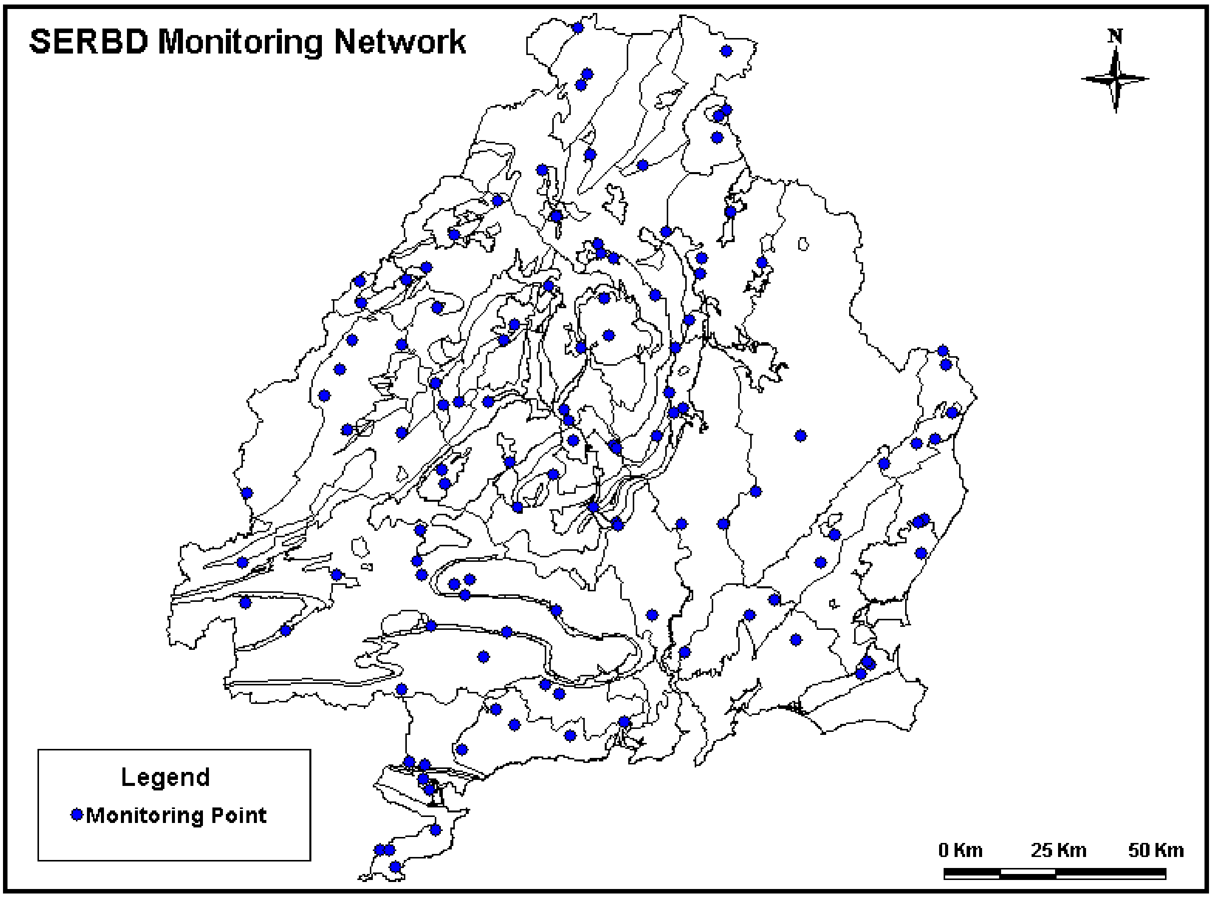

Figure 1.1 Current Groundwater Monitoring Network

2.0 COMPARISON BETWEEN PREDICTIVE RISK ASSESSMENT AND RESULTS FROM GROUNDWATER MONITORING PROGRAMME 2000 - 2004

The Groundwater Risk assessment process and outcomes are discussed in more detail in other papers. As part of the Initial Characterisation process existing groundwater quality data is used to refine the outcomes of the predictive risk assessment process. Such information can only be used for those GWBs where sufficient data is available. This process was particularly useful in the SERBD where there had been sufficient lead in time to undertake a comprehensive review of available data and screening of the monitoring points. Table 2.1 below illustrates how for diffuse source pollutants the predictive risk outcomes were modified as a result of comparison with impact (monitoring) data using nitrate as the typical example of a diffuse pollutant. Nitrate was selected as its impact on groundwater chemical status is very significant in the SERBD.

Table 2.1 Use of Monitoring Data to Modify Risk Assessment Results

	Final Risk		
Predicted Risk	**2b (14%)**	**2a (58%)**	**1b (28%)**
2b (24%)	58.3% remain 2b	51.7% increase from 2b to 2a	
2a (54%)		89% remain 2a	11% increase from 2a to 1b
1b (22%)			100% no 1b increase to 1a

The table shows that more than half (51.7%) of the groundwater bodies defined under the predictive risk assessment process as being not at risk (2b) had their risk level increased to potentially at risk (2a) as a result of the results obtained from the programme. Similarly 11% of the 2a groundwater bodies had their risk level increased from 2a to 1b. None of the 1b groundwater bodies changed risk level to a higher level. Clearly the use of monitoring (impact) data has a significant influence on the outcome of the risk assessment process.

Figure 2.1 below shows the distribution of nitrate levels averaged and weighted over the groundwater body across the SERBD. It should be noted that data is not available for all groundwater bodies (approx 30%). Much of the unmonitored areas represent poorer aquifers. Therefore, the data presented is considered to reflect nitrate levels in the most productive aquifers and those groundwater bodies in the SERBD where groundwater is a significant resource. The data indicates that nitrate levels on average are above the IGV value of 25 mg/l for over 40% of the groundwater bodies currently monitored. The data also indicates levels between 37.5 and 50 mg/l are present in 10 percent of the groundwater bodies. These values represent approximately 32% of the surface areas of the Regionally Important Aquifers in the SERBD.

Prior to using the monitoring data as part of the risk assessment process the following steps were taken: -

- To ensure that the monitoring results are representative of a groundwater body and are consistent with the requirements of the Directive the monitoring results have been averaged across the GWB i.e. mean values of results are used.

- In addition to make the data more representative, given the heterogeneous nature of our aquifers it was suggested by the Groundwater Working Group that the monitoring points are weighted according to their abstraction. This is because larger monitoring points with larger abstractions will have a larger Zone of Contribution and hence be representative of a larger portion of the aquifer (GWG 2004).

- Following the completion of the screening programme and based on guidance outlined by the GWG only groundwater quality data for the past 5 years i.e. from 2000 was used in the characterisation process. Due to changes in nature and level of human activity and the limited data on pressures potentially impacting on water quality before this time period monitoring data from before 2000 was not considered to be a representative measure of the effect of human activity on groundwater quality in the RBD.

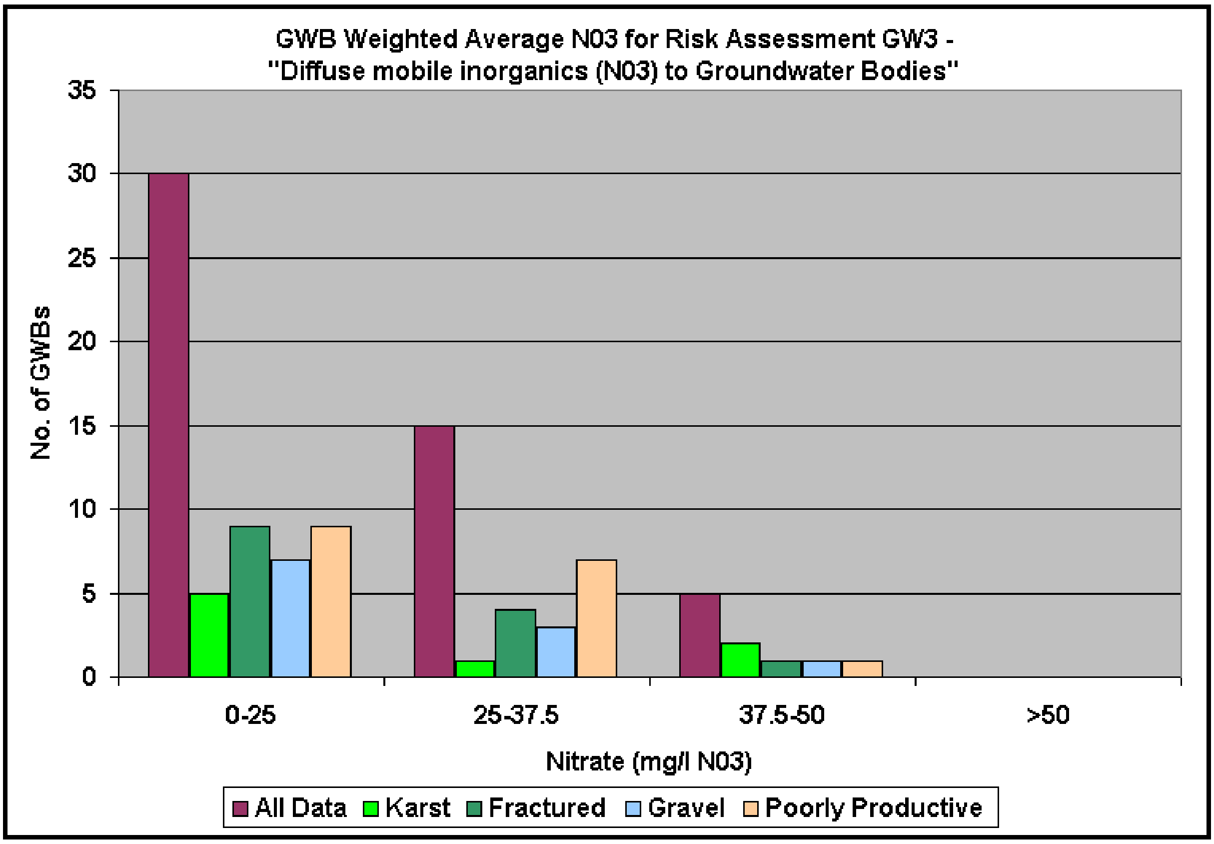

Figure 2.1 Distribution of Nitrate Levels in Groundwater Bodies in SERBD (2000 – 2004)

3.0 MONITORING REQUIREMENTS FOR THE IMPLEMENTATION OF THE WATER FRAMEWORK DIRECTIVE

Guidance on the assessment of available monitoring data and the development of surveillance and operational monitoring networks was prepared by the monitoring sub group of the GWG in 2004. The guidance document incorporates relevant information from similar guidance developed by the UK Technical Advisory Group. This document will be used by the Consultants in all of the RBDs to ensure a consistent interpretation of information and development of the groundwater monitoring programmes on a national basis. The key points from this document are summarised here to illustrate what is required in the development of groundwater monitoring programmes in Ireland for the future implementation of the WFD.

Groundwater monitoring programmes must be established by June 2006 in each RBD. The programmes must incorporate surveillance and operational monitoring networks. In addition, investigative monitoring will be required where GWBs are considered to be at risk of failing to achieve good status as a result of anthropogenic activities which are known to have resulted in contamination.

The Water Framework Directive (WFD) requires monitoring of groundwater chemical and quantitative status. The mandatory chemical status monitoring parameters specified in the WFD are Oxygen content, pH value, Electrical Conductivity, Nitrate and Ammonium. This range of parameters is limited for the purposes of assessing the chemical status of a groundwater body affected by anthropogenic activity and has been expanded upon to complete the Initial Characterisation risk assessment process.

The GWG recommended that for characterisation purposes the parameter range be expanded to include the range of parameters specified in the Environmental Protection Agency Interim Report Towards Setting Guideline Values for the Protection of Groundwater in Ireland, 2003, commonly referred to as the Interim Guide line Values (IGV). The IGV list includes a core list of parameters which can be used to establish the concentration of naturally occurring substances and a second list of site specific or synthetic parameters. The range of parameters on both lists is generally a more extensive range of parameters than is currently being monitoring for as part of the existing local authority or EPA monitoring programmes. The WFD does not require the monitoring of biological water quality. However, monitoring of total and faecal coliforms is incorporated in the expanded list of parameters recommend by the EPA and GWG.

3.1 SURVEILLANCE MONITORING

Surveillance monitoring is carried out in order to: -

- Supplement and validate the procedure for the assessment of pressures and impacts; and
- Provide information for use in the assessment of long term trends both as a result of changes in natural conditions and through anthropogenic activity.
- Surveillance monitoring points may also be used as operational monitoring points and therefore the monitoring points are not mutually exclusive. Surveillance monitoring sites that indicate increased pollutant concentrations or long-term anthropogenic upward trends should also be used for operational monitoring purposes.

In the SERBD the monitoring undertaken over the past 12 months is considered to be surveillance monitoring. The monitoring data will be used to establish an operational monitoring programme for the River Basin District.

The monitoring frequency for surveillance monitoring should be a minimum of twice per year (spring and autumn). The minimum frequency set out in Table 3.1 should be used as a guide.

Table 3.1 Proposed Minimum Monitoring Frequencies for Surveillance Monitoring

		Aquifer Flow Type				
		Confined	**Unconfined**			
			Intergranular flow significant		**Fracture flow only**	**Karst flow****
			Significant deep flows common	**Shallow flow**		
Initial frequency* – core & additional parameters		Twice per year	Quarterly	Quarterly	Quarterly	Quarterly
Long term frequency – core parameters	**Generally high-mod transmissivity**	Every 2 years	Annual	Twice per year	Twice per year	Twice per year
	Generally low transmissivity	Every 6 years	Annual	Annual	Annual	Twice per year
Additional parameters (on-going validation)		Every 6 years	Every 6 years	Every 6 years	Every 6 years	-

* Initial frequency period is defined s a minimum of two years.
** Continuous temperature and conductivity measurements at selected representative sites.

(Source of Table 3.1 and 3.2 *Advice on the Implementation of Guidance on Monitoring Groundwater* in 2004).

3.2 OPERATIONAL MONITORING

Operational monitoring must be undertaken in the periods between surveillance monitoring in order to establish the chemical status of all groundwater bodies determined as being 'at risk', and establish the presence of any long-term anthropogenically induced upward trend in the concentration of any pollutant.

Table 3.2 Proposed Minimum Sampling Frequencies for Operational Monitoring

		Flow Type				
		Confined	**Unconfined**			
			Intergranular flow significant		**Fracture flow only**	**Karst flow**
			Significant deep flows common	**Shallow flow**		
Higher vulnerability groundwater	**Continuous pressures**	-	Twice per year	Twice per year	Quarterly	Quarterly
	Seasonal/intermittent pressures	-	Annual	As appropriate	As appropriate	As appropriate
Lower vulnerability groundwater	**Continuous pressures**	Annual	Annual	Twice per year	Twice per year	Quarterly
	Seasonal/intermittent pressures	Annual	Annual	As appropriate	As appropriate	As appropriate
Trend assessments		Annual	Twice per year	Twice per year	Twice per year	-

The operational monitoring programme will be carried out for all groundwater bodies or groups of bodies that have been identified, through characterisation or through surveillance monitoring, as being 'at risk' of failing to meet the objectives under Article 4. Representative monitoring may suffice for the purpose of groundwater bodies of similar types (in terms of hydrogeological regime and risks located in the recharge area).

Operational monitoring shall be carried out (i) at a minimum of once per year and (ii) between the sampling dates of the surveillance monitoring programme. Table 3.2 above sets out minimum frequency requirements.

4.0 CONCLUSIONS

The existing groundwater monitoring data sets are limited in terms of the range of parameters analysed and the frequency of analysis undertaken for the purposes of GWB characterisation.

More frequent monitoring and a broader range of parameters will have to be incorporated in the surveillance and operational groundwater monitoring programmes which must be implemented by June 2006. The assessment of parameter range and frequency is currently being assessed in the SERBD.

The use of groundwater monitoring data for the SERBD has resulted in a more comprehensive assessment of the risk assessment process as part of the Initial Characterisation process.

Both the predictive risk assessment and the groundwater monitoring results indicate that groundwater chemical status has been affected by diffuse source impacts as reflected in the elevated nitrate levels found in the larger more productive GWBs.

Quantitative status is generally good in the SERBD. As part of further characterisation more detailed assessment of the quantitative status of the Fardystown, Lisheen and Galmoy Mine GWBs will be required in terms of risk from over abstraction and saline intrusion.

Given that 30% of the existing monitoring points in the SERBD are considered unsuitable there will be a need for additional groundwater monitoring points to be incorporated into the existing local authority and EPA programmes to satisfy the requirements of the WFD. The additional monitoring requirements (increased points, frequency of monitoring and range of parameters) will require increased financial resources to sustain these programmes once incorporated into the River Basin Management Plans.

5.0 REFERENCES

EU Stride Environment Sub-Programme Measure 1, *The establishment of a data base for groundwater in the South-East Region of Ireland, Regional Water Laboratory Kilkenny, J Keohane,* 1994.

Environmental Protection Agency, *Interim Report Towards setting guideline values for the protection of groundwater in Ireland, 2003.*

Groundwater Working Group*, Draft Paper Advice on the Implementation of Guidance on Monitoring Groundwater*, 2004.

UKTAG Task 12(a) *Guidance on Monitoring Groundwater(Groundwater Task Team)* 2004.

O'Callaghan Moran & Associates, *Interim Groundwater Monitoring Report for the South Eastern River Basin District* 2005.

OCM would like to acknowledge the support of the SERBD Monitoring Team (Lisa Shiels, Eithne McDevitt, Gary Sweeney, Brid O'Hehir, Claire McLoughlin) under the supervision of Ms. Anthea Southey for their work in the groundwater screening and monitoring programmes since 2003.

RIVER BASIN DISTRICTS - THE FUTURE - MONITORING, CLASSIFICATION AND PROGRAMME OF MEASURES

Pat Duggan, Department of Environment and Local Government

NOTES:

Appendix
IAH Annual Seminars 1981-2004
Catalogue of Presentations and Speakers

Compiled by Geoff Wright, Geological Survey of Ireland

Notes:
The titles of presentations as listed in the Seminar programmes have often differed from the titles as given at the head of the respective paper. I have tried to use the most informative version. The catalogue is as complete and informative as I could make it. I apologise for any inadvertent errors or omissions.

In the interests of brevity, the catalogue omits:
- Titles of speakers (e.g. Dr.)
- Introductory and Closing Remarks, Discussion sessions
- University departments, etc.

Talks for which no paper was produced are in Italics
* Talks for which only an abstract or copies of Powerpoint slides were available

Abbreviations:

BGS	British Geological Survey
DELG	Department of the Environment & Local Government
DEHLG	Department of the Environment, Heritage & Local Government
EPA	Environmental Protection Agency
ERM	Environmental Resource Management
ERU	Environmental Research Unit
GDC	Groundwater Development Consultants, Cambridge
GES	Geotechnical & Environmental Services, Carlow
GSI	Geological Survey of Ireland
GSNI	Geological Survey of Northern Ireland
HES	Hydrogeological & Environmental Services, Belfast
IIRS	Institute for Industrial Research & Standards, Dublin
MCOS	M C O'Sullivan & Co.
NUIG	National University of Ireland, Galway
RTC	Regional Technical College
TCD	Trinity College Dublin
UCD	University College Dublin

1st Annual IAH Seminar
27-28 January 1981, Montague Hotel, Emo, Portlaoise
DEVELOPMENT OF GRAVEL AQUIFERS

Day 1	
Film: 'Ground Water' (National Water Well Association)	*(courtesy Ingersoll Rand Ltd.)*
Occurrence of Gravel Aquifers in Ireland	J R Creighton, GSI
Geophysical Investigations of Gravel Aquifers	Brian Williams, Consultant
Geophysical Investigations: Field Demonstration	*Frank Collar, Minerex*
Drilling and Sampling Gravel Aquifers (1)	Lewis Clark, Water Research Centre
Films: 'World of Water' and 'Revert'	*Johnson Wellscreens*
Drilling and Sampling Gravel Aquifers (2)	Lewis Clark, Water Research Centre
Day 2	
Well Screens and Gravel Packs	*Bill Jungmann, Johnson Wellscreens*
Well Development (with field demonstration)	*Bill Jungmann, Johnson Wellscreens*
Gravel Aquifer Development – Case Histories	*Eugene Daly, GSI; K T Cullen, Consultant *Frank Collar, Minerex; Peter Bennett, GSNI* *Geoff Wright, GSI; *Rod Aspinwall, Consultant* *Lewis Clark, Water Research Centre*

2nd Annual IAH Seminar
30-31 March 1982, Montague Hotel, Emo, Portlaoise
GROUNDWATER DEVELOPMENT IN LIMESTONE AQUIFERS

Day 1	
Irish Limestones	*G D Sevastopulo, Trinity College Dublin*
Irish Limestone Aquifers	Bob Aldwell, GSI
Limestones as Aquifers	*Bill Townsend, USA*
Cable-Tool Drilling in Limestones	*Bill Jungmann, Johnson Wellscreens*
Film: Drilling Methods	
Drilling Methods – Rotary & DTH Hammer Systems	Bill Townsend, USA
Day 2	
Drilling problems: Circulation, Verticality, Well Development	Bill Townsend, USA
Borehole Logging	Bill Townsend, USA
Borehole Logging Demonstration	Eugene Daly, GSI
Sanitary Protection for Water Wells	Bill Townsend, USA
Economic Considerations for Drilling Contractors	*Bill Townsend, USA*

3rd Annual IAH Seminar
19-20 April 1983, Killeshin Hotel, Portlaoise
COST FACTORS IN GROUNDWATER DEVELOPMENT

Day 1	
*Well Design Options	*Bill Jungmann, Johnson Wellscreens
Pumping Costs	Ned Creed, Nicholas O'Dwyer & Partners
Pumping Tests & their uses	Lewis Clark, Water Research Centre
Film	
Optimising Groundwater Development	Lewis Clark, Water Research Centre
Case Histories & Discussion	
Day 2	
Sanitary Protection for Wells	UOP Johnson Wellscreens
Pump Selection, Installation & Maintenance	Tom Ruddy, Electrical & Pump Services Ltd
Groundwater-source Heat Pump Potential in Ireland	John Walls, Energy Management Contractors

4th Annual IAH Seminar
3-4 April 1984, Killeshin Hotel, Portlaoise
GROUNDWATER DEVELOPMENT IN IRELAND - 1984

Day 1	
Legal Aspects of Groundwater	*M Murphy, DELG*
*Groundwater Development in Northern Ireland	*Philip Holland, DoENI
A New Aquifer Map of Ireland	Geoff Wright, GSI
Groundwater Resources of Northern Ireland	Peter Bennett, GSNI
An Approach to Groundwater Development in Co. Meath	Frank Burke, Meath Co. Council
Cooley Groundwater Supply Scheme, Co. Louth	D Gillespie, Nicholas O'Dwyer & Partners
Day 2	
Groundwater Quality and Vulnerability to Pollution – A National Study	Donal Daly, GSI
Health Aspects of Groundwater Quality	Fergus Hill, Dublin Region Public Analyst
Geothermal Resources of Ireland	Bob Aldwell, GSI
Case Histories: Kinvarra, Co. Galway; Moneypoint, Co. Clare;	Kevin Cullen; Stephen Peel, Minerex
Future of Groundwater in Ireland	David Burdon, Minerex

5th Annual IAH Seminar
22-23 April 1985, Killeshin Hotel, Portlaoise
IRISH GROUNDWATER HAS COME OF AGE!

Day 1	
EEC Guidelines for Potable Water	*Diarmuid O'Hegarty, DELG*
Groundwater Treatment	Alec Bowen, Mahon McPhillips
Groundwater Development at Portlaoise	Ned Creed, Nicholas O'Dwyer & Partners
Hydrogeology of the Portlaoise Limestone Aquifer	Kevin Cullen, Consultant
Portlaoise Well Drilling & Test Pumping Programme	Kieran O'Dwyer
Day 2	
Lagan Valley Groundwater Development Project	J Finlay, Kirk, McClure & Morton
Geology of the Lagan Valley	Peter Bennett, GSNI
Geology of the Clonaslee Sandstone Aquifer	Eugene Daly, GSI
Groundwater Development – an Engineer's View	Michael Hand, P H McCarthy & Partners

6th Annual IAH Seminar
22-23 April 1986, Killeshin Hotel, Portlaoise
THE HYDROGEOLOGY AND MANAGEMENT OF LANDFILL SITES

Day 1	
Legislation and Waste Management	Owen Boyle, DELG
Toxic Wastes and Groundwater Contamination	*Stephen Ragone, US Geological Survey*
Landfill Sites and the Environment	Donal Daly, GSI
The Ballyogan Site, Co. Dublin	M Lorrigan, Dublin Co. Council
The Collon Site, Co. Louth	D O'Neill, Louth Co. Council; John Lucas, P O Johnston, Aspinwall & Co.
The Disposal of Industrial Wastes	Emmet McMahon, IIRS
Day 2	
Landfill Assessment Practices	Breda Naughton, An Foras Forbatha
The Silliot Hill Site, Kilcullen, Co. Kildare	D O'Connor, Kildare Co. Council
The Portlaoise Site, Co. Laois	Stephen Peel, Minerex
*A Lined Site in Southern England	*Keith Knox, Cleanaway
An Estuary Site in Belfast	Peter Bennett, GSNI

7th Annual IAH Seminar
7-8 April 1987, Killeshin Hotel, Portlaoise
GROUNDWATER RESOURCES AND QUALITY

Day 1	
Policy for Aquifer Protection	Andrew Skinner, Severn-Trent Water Authority
Aquifer Protection in Ireland: Case Study (1) Clonaslee	Michael Hand, P H McCarthy & Partners
Aquifer Protection in Ireland: Case Study (2) Co. Wexford	Kevin Cullen, Consultant
Septic Tanks and Groundwater	Donal Daly, GSI
Septic Tanks and Public Health	Anne Deacon, SE Health Board
Septic Tanks and Groundwater – Some Recent Irish Research	Richard Thorn, Sligo RTC
Day 2	
The Assessment of Groundwater Resources	Geoff Wright, GSI
Groundwater Investigations in Sandstone Aquifers in North Cork	Paul Walsh, Cork Co. Council
Groundwater Investigations, Co. Wexford	Kieran O'Dwyer
Groundwater Development Overseas: • Introduction / Overseas Consultancy Work / Irish Contributions to International Hydrogeology • Lesotho • Mali • Sudan / Senegal / Iran / Eritrea	 David Burdon, Minerex Ltd Stephen Peel, Minerex Ltd David Ball, ERA Ltd Geoff Wright, GSI

8th Annual IAH Seminar
12-13 April 1988, Killeshin Hotel, Portlaoise
THE FUTURE OF GROUNDWATER DEVELOPMENT IN IRELAND

Day 1	
The Future of Groundwater Development	Glyn Jones, University College London
Groundwater for Public Supply	Phil Callery, Wexford Co. Council
Groundwater for Group Schemes	Tom Geraghty, DELG
Aquifers of the Future: (1) The Mid-Kildare Gravel Aquifer (2) The Kiltorcan Sandstone Aquifer	 Geoff Wright, GSI Eugene Daly, GSI
The Future of Well-Drilling	Brendan Dunne, Dunnes Water Services, Dundalk
New Uses for Groundwater – fish farming, irrigation, bottling, energy	Kevin Cullen, Consultant
Day 2	
Environmental Impact Assessment: The Directive	G Walker, An Foras Forbatha
Environmental Impact Assessment	David Kelly, Eolas
Environmental Impact Assessment: Tara Mines – A Case Study	Bill Dallas, Enviroplan Ltd
Hydrogeology & Environmental Impact Assessment of a Proposed Large Open Cast Mine at Ballymoney	Duncan Finlayson, Hydrotechnica Ltd.

9th Annual IAH Seminar
25-26 April 1989, Killeshin Hotel, Portlaoise
GROUNDWATER CHEMISTRY AND GROUNDWATER FOR THE BOTTLED WATER AND AQUACULTURE INDUSTRIES

Day 1	
Natural Chemistry of Groundwater	Eugene Daly, GSI
Variations in Groundwater Quality	Richard Thorn, Sligo RTC
Groundwater Monitoring	Catherine Coxon, TCD
Approaches to Aquifer Protection	Donal Daly, GSI
Standards and Certification for Bottled Waters	Richard Foley, Eolas
The Bottled Water Boom	Timothy Green, co-author/publisher of 'The Good Water Guide'
Geology and Chemistry of Various Bottled Waters	Peter Bennett, GSNI; Stephen Peel, Minerex; Eugene Daly, GSI
Bottled Water – The Irish Experience	Brian Duffy, Glenpatrick; *Geoff Read, Ballygowan*
Day 2	
Water Quality for Farmed Salmonids	Gerard Morgan, University College Cork
Groundwater Sources for Fish Farming	Kevin Cullen, Consultant
Fish Farming in Ireland – An Overview	Pat Timpson, Sligo RTC/Fish Farmer
The Business of Aquaculture	Liam Kielthy, National Development Corporation

10th Annual IAH Seminar
1-2 May 1990, Killeshin Hotel, Portlaoise
CLIMATIC EXTREMES AND THEIR EFFECT ON WATER RESOURCES

Day 1	
Short Term Prospects for Global Climate and their Implications for Irish Regional Precipitation Yields	John Sweeney, St Patrick's College, Maynooth
Climatic Extremes and the Irish Climate	Irish Meteorological Service
River Flows: Existing Practice and Climate Change	John Martin, Office of Public Works
Potential Effects of Climatic Extremes on River and Lake Quality	Martin McGarrigle, ERU
The Likely Effects of Significant Climatic Changes on the Flow Regime in the Principal Irish Aquifers	Eugene Daly, GSI
Climate Change, Meteorological Extremes and Groundwater Quality	Richard Thorn, Sligo RTC
Flood Warning and Prevention in Co. Kilkenny	Harry Shine, Office of Public Works
The Structure of Flood Flow in Rivers with Floodplains	Ger Kiely & E J McKeogh, UCC
Drought and Water Resources – the Sub-Saharan Experience: Coping with Limited Water Resources – What We Can Learn from Arid Areas	David Ball, ERA-MapTec
Day 2	
Implications of Climatic Change for Agriculture	Tom Keane, Irish Meteorological Service
The Local Authority Experience: • The Implications of Climate Change for County Wexford • County Westmeath	 Phil Callery, Wexford Co. Council; Tom Fitzpatrick, Westmeath Co. Council
Extreme Floods on ESB Hydro Catchments	Thomas Hayes, ESB
Floods and Low Flows – the UK Experience	Rick Brassington, National Rivers Authority

11th Annual IAH Seminar
9-10 April 1991, Killeshin Hotel, Portlaoise
GROUNDWATER ASPECTS OF ENVIRONMENTAL IMPACT ASSESSMENTS

Day 1	
Current EIA Legislation in Ireland	Pat Timpson, National Water & Waste Institute
EIAs and Groundwater	Catherine Coxon, TCD
Agriculture, Groundwater and EIA	Richard Thorn, Sligo RTC
*Industry, Groundwater and EIA	*Kevin Cullen, Consultant
Waste Disposal, Groundwater and EIA	Shane O'Neill, ERA-MapTec
Mining, Quarrying, Groundwater and EIA	Eugene Daly, GSI
EIAs and Groundwater – the US Experience	Ron Hoffer, US EPA
Day 2	
Wellhead Protection in the US	Ron Hoffer, US EPA
Aquifer Protection in Europe	Bob Aldwell, GSI
Groundwater Protection in Ireland	Donal Daly, GSI
An Aquifer Protection Policy for Co. Wexford	Thomas Hoare, Wexford Co. Council

12th Annual IAH Seminar
7-8 April 1992, Killeshin Hotel, Portlaoise
GROUNDWATER AND REGIONAL WATER SUPPLY

Day 1	
Overview of Status of Regional Water Supplies in Ireland	Gerry Galvin, Nicholas O'Dwyer & Partners
The Status and Potential of Large Ground Water Abstractions	Don O'Sullivan, Wexford Co. Council
The Groundwater Resources of Ireland	Bob Aldwell, GSI
Indirect Methods: Remote Sensing and Geophysics	Jer Keohane, Fugro-McClelland
Pumping Tests	Kieran O'Dwyer, K T Cullen & Co.
Modelling – Aquifer Vulnerability; Well Head Protection; Management of Resources	*Colin Smith, Consultant*
Interaction of Large Groundwater Abstraction, Legislation, Treatment and Economics	*Dave Cooke, Thames Water Utilities*
Day 2	
Assessment of Water Balance for Regional Water Resources	*David Ball, Consultant*
Case Study of Assessment of Water Resource of an Irish River Catchment	*Tommy Bree, ESB International*
Overview of Statutory Regulations in Relation to Water Quality	P J Flanagan, ERU
Microbiology Aspects of Groundwater Quality	Ronnie Russell, TCD; Richard Thorn, Sligo RTC
Results of Recent Trihalomethane Study of Public Water Supplies	Ciaran O'Donnell, ERU
Interpretation of a 'Typical' Water Analysis	Richard Foley, Eolas
Trade Talk on the Treatment of Iron and Manganese	Michael Boole, Halpin & Hayward

13th Annual IAH Seminar
20-21 April 1993, Killeshin Hotel, Portlaoise
BASIN MANAGEMENT & INFORMATION TECHNOLOGY – AN AID TO REGIONAL PLANNING

Day 1	
Water Management, Monitoring and Information Systems	Jan Boswinkel, TNO, Netherlands
Groundwater Monitoring in Northern Ireland	Peter Bennett, HES, Belfast
Catchment Monitoring & Management	G A Burrow, National Rivers Authority
Ardnacrusha and Management of the Shannon Catchment	A Shaw, ESB
Data Monitoring for Environmental Engineering Systems	Sean McCarthy, Hyperion Energy Systems
Data Processing & Manipulation	Tom Joyce, Office of Public Works
River Flow Modelling – An Introduction	R Kachroo, University of Dar Es Salaam / University College Galway
Day 2	
Hydrogeology of Dolomite Aquifers of SE Ireland	Eugene Daly, GSI
Large Scale Pumping Tests	Kieran O'Dwyer, K T Cullen & Co.
Groundwater Development in North Cork	Pat Walsh, Cork Co. Council
Review of Legislation Relating to the Quality of Groundwater	Owen Boyle, DELG
Grey & Black List Substances	T O'Flaherty, Eolas
Geographical Information Technology and Data Management: Putting Flesh onto Data	David Moore, NGIS Ltd

14th Annual IAH Seminar
19-20 April 1994, Killeshin Hotel, Portlaoise
WATER POLLUTION – LAW, PRACTICE AND PLANNING

Day 1	
Aspects of the Law relating to Groundwater Pollution	Yvonne Scannell, TCD
Civil Liability for Groundwater Pollution: the Cambridge Water Company Case	Bruce Misstear, Paul Ashley, GDC
Case Histories & Experiences • Sewerage Legislation in Ireland • Wicklow County Council • The Trophic Status of Lough Conn, Co. Mayo • Dublin Corporation Drainage Division • Control of Groundwater Pollution in Northern Ireland	 Martin Lavelle, Cork Co. Council Muiris O'Keeffe, Dublin Co. Council Siobhan Sheil, NW Regional Fisheries Board Anthony Foy, Dublin Corporation Des Lyness, DoE NI
Water Pollution and Planning	John Reid, Reid Associates
Day 2	
Consistency of Laboratory Data	C Concannon, EPA
Mallow Natural Energy Centre	Pat Walsh, Cork Co. Council
Impact of Geology on Groundwater Quality Natural Impurities in Groundwater: Northern Ireland Groundwater Carbon Dating	Kevin Cullen, Consultant Peter Bennett, HES David Ball, Consultant
Bottled Water and Public Awareness	Dermot Byrne, Bottled Waters Association of Ireland

15th Annual IAH Seminar
25-26 April 1995, Killeshin Hotel, Portlaoise
THE ROLE OF GROUNDWATER IN SUSTAINABLE DEVELOPMENT

Day 1	
Our Geological Heritage is Worth Sustaining	Peadar McArdle, GSI
Integrating Environment and Development – the Use of Pricing and Other Incentives to Achieve Efficient Use of Environmental Assets	Frank Convery, UCD
The Principal Characteristics of the Flow Regime in Irish Aquifers	Eugene Daly, Eugene Daly Associates
Groundwater Protection in Ireland: a Scheme for the Future	Donal Daly, GSI
The Role of Modelling in Groundwater Source Protection	Paul Johnston, TCD
EPA Landfill Manuals	Gerry Carty, EPA
The Engineering of Landfill	Jonathan Derham, MCOS
Landfill Studies: The Role of the Hydrogeologist	Suzanne O'Sullivan, Consultant
Day 2	
Trace Organics in Irish Groundwaters	Shane Bennet, K T Cullen & Co.
Landspreading of Animal Wastes	Billy Moore Tipperary (SR) County Council
Regional Lecture*:* Occurrence and Distribution of Groundwater in Northern Ireland	Nick Robins, British Geological Survey
Implications of Sewer Development on Groundwater Quality	Bruce Misstear, TCD; Philip Bishop, Mott MacDonald Group
Sustainable Groundwater Sources	David Ball, Consultant

16th Annual IAH Seminar
23-24 April 1996, Killeshin Hotel, Portlaoise
WATER WELLS – DRILLING, DESIGN, CONSTRUCTION, OPERATION & MAINTENANCE

Day 1	
A Review of Groundwater Development in Ireland	Kieran O'Dwyer, K T Cullen & Co.
The Design and Construction of Water Wells in Ireland	David Ball, Consultant
Water Wells – Monitoring, Maintenance and Rehabilitation	Peter Howsam, Cranfield University
Estimating the Reliable Output of Water Wells	Bruce Misstear, TCD; Sarah Beeson, Jan van Wonderen, GDC
Location & Development of a Major New Limestone Aquifer in Co. Cork	Brian Connor, Consultant
Assessment of the Potential of Developing a Groundwater Source at Ardmore, Co. Waterford	Jer Keohane, GES
Roscommon Central Regional Water Supply Scheme – Development of the Ballinagard Aquifer	Conor McCarthy, Jennings O'Donovan & Partners
Casings and Screens	Thomas Fogarty, Fogarty Drilling
Day 2	
Achieving Groundwater Protection	Aidan Briody, Briody's Aquadrill Services
*Case History: Gravel Aquifer Investigations in the Glen Swift Valley, Letterkenny, Co. Donegal	*Cecil Shine, Minerex Environmental
An Introductory to the Hydrofracturing of Water Wells	Des Meehan, Well Driller
Protection of Public Groundwater Sources	Donal Daly & Jenny Deakin, GSI
Regional Lecture: Groundwater Conditions in the Limestones of Eastern County Galway	David Drew, TCD
Well Performance Tests – Their Use in Borehole Management	Shane O'Neill, TCD
Water Wells: Contracts and Specifications	Eugene Daly, Eugene Daly Associates

17th Annual IAH Seminar
22-23 April 1997, Killeshin Hotel, Portlaoise
SOIL AND GROUNDWATER CONTAMINATION AND REMEDIATION

Day 1	
The Soil System Viewed as an Active Element in the Clean-up and Control of Contaminated Land	Michael Bloxham, Grondmechanica Delft
The Protection of Groundwater Quality in the UK – Present Controls and Future Issues	Bob Harris, Environment Agency
Non-Aqueous Phase Liquids: Investigation and Remediation	Paul Johnston & Bruce Misstear, TCD
Practical Site Investigation of Contaminated Land & Groundwater	Jer Keohane, Geotechnical & Environmental Services
Groundwater Monitoring – Fact or Fiction	Teri Hayes, K T Cullen & Co.
Making Remediation Work – Practical Design Considerations	Andrew Moag, Aspinwall & Co.
The Hydrogeology of Avoca Mines	Donal O Suilleabhain, BMA; Bruce Misstear, TCD; Geoff Wright, Pat O'Connor, GSI
Day 2	
Pulverised Fuel Ash: Its Composition and Weathering	Simon Pow, ESB International
Geophysics or Drilling – Which should come first in a Contaminated Land Investigation?	Richard Church, Minerex Environmental
European Initiatives for Assessment and Action on Contaminated Land	Matt Crowe, EPA
Risk Based Decision Making at Chemical Release Sites: Soil and Groundwater Pathway	Marcus Ford, Dames & Moore, Ireland
Solutions to Leaking Home Heating Oil Systems	Shane Bennet, Contaminant Hydrogeologist
Regional Lecture: Groundwater in the South Munster Region	Geoff Wright, GSI
COSIMA – Contaminated Sites Management Support System	Maura Minogue, John Flynn, Cork Corporation

18th Annual IAH Seminar
21-22 April 1998, Killeshin Hotel, Portlaoise
HYDROGEOLOGY AND WASTE MANAGEMENT

Day 1	
A Conceptual Design for Sustainable Landfill	Nick Walker, Cleanaway Ltd; R P Beaven, W. Powrie, University of Southampton
Dealing with Uncertainty in the Assessment of Groundwater Impacts from Landfills: The LandSim Model	David Hall, Golder Associates
Integrated Pollution Control, Licensed Industrial Activities – Waste Management	Jonathan Derham, Becci Cantrell, EPA
Hydrogeology of Magheramourne Quarry, and Northern Ireland Landfill Legislation	Peter Bennett, HES
Landfills: Assessing and Managing the Long Term Risk and Liabilities	Geoff Parker, K T Cullen & Co.
Licensing of Waste Recovery and Disposal Activities	Gerry Carty, EPA
Landspreading of Organic Wastes and Groundwater Protection	Donal Daly, GSI; Vera Power, Margaret Keegan, EPA
Landspreading of Organic Wastes: Selected Case Studies	Richard Church, Minerex Environmental
Day 2	
Waste Management Strategy for the Dublin Region	P J Rudden, MCOS
Water and Environmental Health – The Wider Dimensions	Anne Deacon, SE Health Board
Constructed Wetlands for Wastewater Management	Ciaran Costello, Maxpro Engineering
Septic Tank Systems: Recent Advances	Hubert Henry, Bord na Mona Environmental
Mining Waste and the Groundwater Environment	James Dodds, Steffen Robertson Kirsten
Regional Lecture: Groundwater Modelling in the Karst Limestones of the Gort Lowlands	Paul Johnston, TCD; Denis Peach, BGS

19th Annual IAH Seminar
20-21 April 1999, Killeshin Hotel, Portlaoise
SURFACE WATER AND GROUNDWATER: A COMBINED RESOURCE

Day 1	
Keynote Lecture: Groundwater and Surface Water Relationships in the USA	Patrick Leahy, US Geological Survey
Groundwater Resource Management in England and Wales: A Quest for Sustainable Development	David Burgess, Environment Agency
Integrated Surface Water and Groundwater Modelling	Peter Rippon, Mott MacDonald
Nitrates in County Offaly	Des Page, Jack Keyes, Offaly County Council
Groundwater and Surface Water: Exploiting a Combined Resource	Bruce Misstear, TCD
Water Quality Management Planning	Andy Fanning, EPA
Catchment Monitoring and Management Systems	Ciaran O'Keeffe, MCOS, Colin Byrne, Ray Earle, Three Rivers Project
Day 2	
Influent Rivers: A Pollution Threat to Spring Water Supplies	Steve Hobbs, Andrew Moag, Aspinwall & Co.
Drainage, Runoff, and Vulnerability Maps	Monica Lee, TCD & GSI
Groundwater and Surface Water Relationships in Karst Terrain	Catherine Coxon, David Drew, TCD
The Contribution of Groundwater Phosphorus to Surface Water Eutrophication	Garrett Kilroy, TCD
Water Strategy for Kildare: The Consultants' Report	Teri Hayes, KT Cullen & Co.; Tommy Farrell, Nicholas O'Dwyer & Partners
Isotopes as a Measure of Surface Water Infiltration: A Case Study in Northern Ireland	Ciara McConville, Doran & Partners; Bob Kalin, Queens University Belfast

20th Annual IAH Seminar
11-12 April 2000, Killeshin Hotel, Portlaoise
GROUNDWATER AND THE LAW: DIRECTIVES, STANDARDS & REGULATIONS

Day 1	
Keynote Lecture*:* The EU Water Framework Directive	James Hunt, Environment Agency
*The EU Water Framework Directive in Ireland	*David Moore, DELG
Groundwater Aspects of the Nitrates Directive	Vincent Fitzsimons, GSI
Groundwater Jurisdiction: A Canadian Perspective	Ken Howard, University of Toronto
Groundwater Issues in Planning	Padraig Thornton, An Bord Pleanàla
Planning and Groundwater Supply	*Fergus Coyle, Monaghan Co. Council*
Groundwater in the Court, or Common Logic vs. Hydrogeological Concepts	Kevin Cullen, K T Cullen & Co.
The Need for a National Well Standard and Suggested Content	David Ball, Consultant
*Groundwater and India	*Kalpana Unadkat, Ashurst Morris Crisp, London
Day 2	
Groundwater Quality Standards in the Netherlands: Derivation and Application	J P A Lijzen & F A Swartjes, National Institute for Public Health & Environment
Groundwater Quality Standards in Germany	Lutz Haamann, Degussa-H ls AG
Contaminated Land: Groundwater Quality Standards in the UK	Barry Smith, British Geological Survey
The Development of Guideline and Intervention Values for the Protection of Groundwaters in Ireland	Margaret Keegan, Gerard O'Leary, Garry Carty, EPA
Groundwater and the Law: A Consultant's Perspective	*Eugene Daly, Eugene Daly Associates*
The Implications of the EU Commission White Paper on Environmental Liability for Irish Environmental Law	Yvonne Scannell, Arthur Cox & Associates
Groundwater and the Law: An Historical Perspective	*Peter Bennett, HES*

21st Annual IAH Seminar
16-17 October 2001, Tullamore Court Hotel, Tullamore
GRAVEL AQUIFERS: INVESTIGATION, DEVELOPMENT & PROTECTION

Day 1	
A Review of Gravel Aquifers in Ireland	Geoff Wright, GSI
Keynote Paper: International Perspectives on Gravel Exploitation	Charles Jones, Mott MacDonald
Production Well Operation in Gravel	Kees van Beek, Netherlands Waterworks Testing & Research Institute
Geophysical Methods for the Investigation of Gravel Aquifers	Peter O'Connor, APEX Geoservices
Remedial Options for a Diesel-Contaminated Confined Gravel Aquifer	Graham Webb, URS Dames & Moore
The Role of Sand & Gravel Deposits in Vulnerability Assessment and Mapping	Donal Daly, GSI
Source Protection Issues – Scotland	Charles Jones, Mott MacDonald, Cambridge
Gravel Aquifers – Integration of Groundwater Development and Source Protection	Kieran O'Dwyer, K T Cullen & Co.
Day 2	
The Curragh Aquifer – Current Conceptual Understanding and Numerical Modelling	Teri Hayes, Kevin Cullen, K T Cullen & Co.; Stuart Sutton, John Faherty, Entec UK
KTK Landfill – Investigations, Leachate Management and Groundwater Modelling	Mark Heesom, KTK Landfill; Geoff Parker, ERM
Contamination and Remediation in Gravels – Sir John Rogerson's Quay Gasworks, Dublin	Mark Adamson, Parkman Environment
Gravels and Planning: Rural Blessing and Urban Problem	David Ball, Consultant

22nd Annual IAH Seminar
16-17 April 2002, Tullamore Court Hotel, Tullamore
GROUNDWATER QUALITY: CURRENT ISSUES AND CONCERNS

Day 1	
Water Framework Directive – An Overview of Groundwater Aspects	Donal Daly, GSI
The Water Quality of Groundwater – Chapter 5 Water Quality in Ireland 1998-2000, EPA	Margaret Keegan, Becci Cantrell, Micheal MacCarthaigh, Paul Toner, EPA
Nitrate Vulnerable Zones – Latest Developments	Pat Duggan, DELG
The Drinking Water Regulations 2000 – Outline of Requirements	Richard Foley, Enterprise Ireland
Groundwater Quality – A Question of Perspective	Kieran O'Dwyer, White Young Green
Keynote Paper: Current Knowledge of Groundwater Microbial Pathogens and Their Control	Bruce Macler, Jon Merkle, US EPA
Group Water Scheme Bacteria Problems – A Local Authority Perspective	Ray Spain, Offaly County Council
Day 2	
Groundwater Quality – Sampling and Analysis	Peter Webster, EPA Cork
In Situ Bioremediation of High Nitrate Chalk Aquifers	Paul Godbold, WRc Plc, UK
Problems with Iron and Manganese	Jer Keohane, GES, Carlow
Keynote Paper: The Use of Monitored Natural Attenuation as a Cost-Effective Technique for Groundwater Restoration	David Lerner, Steven Thornton, Ruth Davison, University of Sheffield
Case Studies in Monitored Natural Attenuation	Alistair Wyness, Richard Bewley, URS,
Permeable Reactive Barriers	Alan Thomas, ERM, Oxford

23rd Annual IAH Seminar
29-30 April 2003, Tullamore Court Hotel, Tullamore
GROUNDWATER: ITS STAKEHOLDERS

Day 1	
Protecting Groundwater in US Communities – The Groundwater Guardian Program	Susan Seacrest, The Groundwater Foundation
The City of New York Water Supply – Watershed Management	Richard I Coombe, Watershed Agriculture Council, New York State
The Three Rivers Project – Boyne, Liffey & Suir – Involving Stakeholders in Water Management	Suzanne Dempsey, MCOS
EPA Oral Hearings and Groundwater	Dara Lynott, EPA
Site Suitability Assessments for On-Site Wastewater Management: a Multi-disciplinary Training Course	Donal Daly, GSI
Groundwater Group Schemes: Past, Present & Future Problems	Pat Harrington, John Carley, Carlow Co. Council
Groundwater Issues - the Farmer's Perspective	Matt Dempsey, Irish Farmers Journal
The Economic and Environmental Importance of Ground Water – Education Programs that work for Citizens, Communities and Decision-Makers	Andrew Stone, American Ground Water Trust
Irish Hydrogeology and Third-Level Education	Bruce Misstear, TCD
Professional Registration and CPD	Kevin Cullen, White Young Green / IGI
Day 2	
The Role of Hydrogeologists in Africa	*Cecil Shine, Minerex Environmental*
Groundwater and Rural Water Supply in Sub-Saharan Africa	Alan MacDonald, BGS
Concern Projects in the Developing World	Niall Roche, Concern Worldwide
Groundwater and Water Resources Development in Uganda – an African Perspective	Callist Tindimugaya, Ministry of Water, Lands & Environment, Uganda
Water, Sanitation and Health in Uganda – Important Changes for Donors, Government Agencies, Communities and the Private Sector	Jacinta Barrins, NUIG
Water Projects and Issues in the Developing World	David Ball, Consultant
David Burdon Memorial Lecture: The Role of Hydrogeology in Rebuilding Afghanistan	David Banks, Holymoor Consultancy

24th Annual IAH Seminar
20-21 April 2004, Tullamore Court Hotel, Tullamore
GROUNDWATER CHALLENGES OF THE NATIONAL DEVELOPMENT PLAN

Day 1	
The National Development Plan and Spatial Strategy: Current Requirements and Future Challenges for the Groundwater Community	*Niall Cussen, DEHLG*
Hydrogeology and the Future of Irish Planning	Conor Skehan, Dublin Institute of Technology
Proposed Infrastructure Developments: The Requirements and Expectations of An Bord Pleanàla that would assist in an Effective Implementation of the NDP	*Brian Hunt, An Bord Pleanàla*
A County Engineer's perspective of Groundwater Issues in, the Planning Process	Billy Moore, ex-Monaghan Co. Council
The Role of An Taisce in Groundwater and Planning Issues	Tony Lowes, An Taisce
The Developer's Perspective with Regard to Power Generation and the Hydrogeology of Upland Areas	*Brendan Layden, Arigna Fuels*
Source Protection Strategies for Group Water Schemes	Maurice O'Connell, M J O'Connell & Co.
Improving Groundwater Supplies in Rural Areas using Design Build and Operate Contracts	Liam Clear, T J O'Connor & Associates
The Role of the Geological Survey of Ireland in Supporting Groundwater Resource Development	Geoff Wright, GSI
Day 2	
Groundwater Challenges in Waste Management	Ted Nealon, A1 Waste
Contaminated Land & Risk Assessment: The Basics	Malcolm Doak, EPA
Brownfields and Urban Sustainability	Niamh Moore, UCD
Assessing the Risks, Costs and Benefits of Managing/Redeveloping Contaminated Sites	Simon Firth, Rob Bracken, Jane Dottridge, Komex
Groundwater Challenges for the National Roads Authority	Michael Egan, National Roads Authority
Potential Impacts of Road Infrastructure on Groundwater and Sensitive Environments – Lessons Learnt from Developments to Date	*Jim Ryan, Duchas*
*Case Study of Groundwater Challenges of Road Construction in a Karst Environment	*Anita Furey, Tobin Consulting Engineers, Alistair Moseley, Hyder Consulting