INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

presents

GRAVEL AQUIFERS: INVESTIGATION, DEVELOPMENT & PROTECTION

PROCEEDINGS

OF THE

21ST ANNUAL IAH (IRISH GROUP)

GROUNDWATER SEMINAR

VENUE:

Tullamore Court Hotel, Co. Offaly.

DATES:

Tuesday 16th & Wednesday 17th October 2001.

2001 IAH (Irish Group) Tullamore Seminar Organising Committee:

ISSN - 1393-1806.

Cover designed by David Ball.

Published by: International Association of Hydrogeologists (Irish Group)
Malcolm Doak PGeo
Inspector
Environmental Protection Agency
PO Box 3000
Johnstown Castle Estate
Co. Wexford.

Whilst available, copies of these Proceedings can be purchased for €35 (plus postage €3) by application to the above address.

Many thanks to Susan Molloy of K.T. Cullen & Co. for her help in administering conference registration and to Róisín De Búrca of the GSI for her help in the preparation of the Proceedings.

Table Of Contents

The following papers are ordered in their sequence of presentation:

FOREWORD

Gravel aquifers constitute an important, if under-utilised groundwater resource in Ireland. Limited experience with, and understanding of, proper drilling and investigation techniques in gravel are often cited as reasons why some groundwater development projects have tended to ignore gravel bodies. The objective of the seminar is to increase the awareness and understanding of gravel aquifers amongst drillers, engineers, and hydrogeologists and amongst their potential clients. Emphasis is placed on Irish gravel aquifers, encompassing issues such as exploration and development practices, groundwater protection, and contamination. Case studies are presented by experts using data from some of the major Irish hydrogeological and infrastructural projects. An international perspective is provided by two invited speakers from the UK and the Netherlands.

The Irish Group of the IAH was initiated in 1976 and celebrates its 25th Anniversary this year with over 90 members. It hosts an annual groundwater seminar 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 offices in Dublin. This year is a double celebration since our first seminar was held 21 years ago and dealt with gravel aquifers. As a timely review in this our 21st seminar we will again deal with gravel aquifers.

Vincent Fitzsimons
Geological Survey of Ireland.

1. A Review of Gravel Aquifers in Ireland

Geoff Wright, Senior Hydrogeologist, Geological Survey of Ireland.

A REVIEW OF GRAVEL AQUIFERS IN IRELAND

Geoff Wright
Geological Survey of Ireland

Abstract

Across the world, gravel aquifers account for more than half of total groundwater abstraction. However, twenty years after our first annual IAH Seminar was held at the Montague Hotel, Portlaoise, on the theme of 'Gravel Aquifer Development', Irish gravel aquifers remain relatively unappreciated and underdeveloped.

Gravel aquifers occur in Ireland in a variety of geological environments and are exploited not only by boreholes but also by springs, dug wells, infiltration galleries and well points. Among the notable advantages of gravel aquifers are their high permeabilities, high storage coefficients, good filtration and attenuation characteristics and low flow velocities. Among their perceived disadvantages are their generally high vulnerability and the greater skill, time and patience required for good well construction.

The knowledge and skills required to design and construct efficient bored wells in gravel aquifers ***can*** *be found within both the hydrogeological profession and the well-drilling industry. As the aquifers become better defined, I hope that these skills will be increasingly employed to provide sustainable sources of good quality water.*

INTRODUCTION

Twenty years ago, we held the first of what came to be known as the "Portlaoise Seminars", which became the major event in the IAH Group's annual calendar. It was held, not in the Killeshin, but in the Montague Hotel, a few miles up the road from Portlaoise, and it was in late January rather than the mid-April date we later settled on. Both the venue and the date were significant. The January date was chosen because our first two seminars were aimed as much at well-drillers as engineers, and the winter is the least busy time for the well-drilling profession. And the Montague Hotel was chosen because we knew that it was located on a gravel aquifer – Kevin Cullen had personally supervised the drilling of a well there just the year before, and a few months before the seminar, I assisted Eugene Daly with a little geophysical resistivity survey in the hotel grounds. The theme of the seminar was "The Development of Gravel Aquifers", and on the second afternoon we had a drilling demonstration beside the hotel car park.

We didn't intend to initiate an annual event. The 1981 seminar might have been a one-off. We simply wanted to spread a positive message about developing gravel aquifers. We had no idea how many people would turn up. As it happened, perhaps because the cost was low (£20 a head) we got about 120 people, and were encouraged enough to try again the next year. The rest, as they say, is history.

But why 'Gravel Aquifers'? In the early 1970s, before coming to work in Ireland, I had been involved with developing gravel aquifers in several countries. When I arrived here I got involved with some gravel aquifer projects and I became aware that, in general, gravel aquifers were not developed properly in Ireland. So I wondered how we might try to improve things. Then in 1979, Douglas Gordon and Atlas Copco organised a very well attended and successful meeting in Limerick, mainly demonstrating their new ODEX method of drilling through 'overburden' into hard rock aquifers. I asked if Atlas Copco could repeat the exercise for gravel aquifers, but despite Douglas's best efforts, they declined. So it was that IAH began the sequence of annual seminars which have now completed a second decade, and here we are....................

GRAVEL AQUIFERS WORLDWIDE

Gravel aquifers were probably the first to be exploited by early civilisations: the first wells were probably shallow holes scooped in the bed of a recently dried-up river. Temporary wells like these can still be found in many countries. Later, people would have discovered that a well dug on the river bank or terrace could have a longer life, especially if lined with wood or stone.

Over time, methods of excavation and well construction became increasingly sophisticated, as did methods of raising water – progressing from simple buckets and *shadufs* to water wheels, hand pumps and centrifugal pumps. As it became possible to raise larger quantities, irrigation became a major user of groundwater.

Today, across the world, gravel aquifers are still the commonest aquifers developed and account for more than half of total groundwater abstraction. Yet in Ireland, they are relatively unappreciated and underdeveloped, and most wells are drilled into hard rocks. Some possible reasons for this are considered later in this paper.

GRAVEL AQUIFER CLASSIFICATION IN IRELAND

In our county groundwater protection schemes, the GSI applies a number of basic criteria for the identification of gravel aquifers:

- A gravel (or sand/gravel) deposit which has sufficient permeability to be considered an aquifer (roughly $>10^{-4}$ m/s) will normally have a silt/clay fraction below about 7%, and typically less than 5% (Ó Súilleabháin, 2000).
- A gravel (or sand/gravel) deposit needs to have an area of at least one square kilometre to be considered an aquifer (occasional exceptions may occur).
- A gravel (or sand/gravel) aquifer normally needs *either* a saturated thickness of at least five metres *or* a total thickness of at least ten metres (where information on saturated thickness is unavailable).
- Gravel Aquifers may be classified as either regionally important or locally important aquifers, based mainly on their regional extent. To be considered as regionally important, an area of at least 10 square kilometres is normally required.
- The continuity of a gravel aquifer is also important in considering its classification.

GRAVEL AQUIFER OCCURRENCE IN IRELAND

Irish gravel aquifers were deposited during the Quaternary period of our geological history, i.e. within the last 1,600,000 years, or what is commonly known as the Ice Age. During this period Ireland was subjected to a number of glaciations, interspersed with warmer spells (interglacials). Most Quaternary deposits in Ireland were laid down during the last glaciation, which took place between about 70,000 and 10,000 years ago (Tipperary (SR) County Council/GSI/FÁS, 1998). The deposits can be broadly classed as:

- Glacial (deposited more or less directly from the ice, and therefore relatively unsorted and less permeable)
- Glacio-fluvial (deposited by running water beneath or downstream of the ice, therefore better sorted and more permeable)

Since the last glaciation about 10,000 years ago, other sand and gravel deposits have been laid down by rivers and along our coasts.

As a result of these various geological processes, gravel aquifers in Ireland are found in a variety of geological environments (Creighton, 1981):

- Buried valleys
- Outwash fans
- Eskers
- Moraines
- Alluvial gravels and river terraces
- Raised beaches
- Dunes
- Pockets in the irregular surface of karst limestones

BURIED VALLEYS

At times during the Quaternary period, the sea level around Ireland was much lower than today, and rivers were able to erode their valleys to considerable depths below present sea level. Subsequently, these deep valleys have been largely backfilled by a variety of sediment, much of which can be highly permeable sand and gravel.

The gravel aquifers found in buried valleys are some of the most successfully developed to date. Two examples, in Tallaght, Co. Dublin, and Carrigtwohill, Co. Cork, are discussed later in this paper.

Buried valley aquifers have many advantages: their depth, and a shallow water table, usually gives plenty of available drawdown. They often have a good thickness of silty or clayey deposits above the gravel, which provides protection from local contamination, and the valley situation usually ensures plenty of recharge from adjacent hill slopes. Their main disadvantage is probably that they can be difficult to find and delineate. In the two case studies given, preliminary indications were provided by 'wildcat' boreholes, but the topographic situation usually gives a clue, and if this local borehole records indicate good depths to bedrock (say, over 20 metres over a significant area), then exploratory drilling will often be worthwhile.

OUTWASH FANS

These deposits take the form of fans of stream debris dropped at the glacier front via drainage channels. Deltaic deposits are similar but form deltas where the drainage channels discharge into a standing body of water. The deposits are primarily composed of coarse, well-rounded, gravels with sand, and may be poorly or well sorted.

Perhaps the most extensive, best-known and potentially most productive gravel aquifer in Ireland is the one which underlies the Curragh - what I have termed the 'Mid-Kildare Gravel Aquifer', to emphasise that it extends far beyond the bounds of what most people understand by 'The Curragh' (Wright, 1988). The stratigraphic sequence, around 60 metres thick, is by no means entirely gravel, but is certainly gravel-dominated.

Other extensive outwash deposits are found in the Blessington area of County Wicklow, where a thickness of over 100 metres is recorded, and elsewhere in the country.

ESKERS

Eskers are long, relatively narrow (commonly 30 – 100 metres wide), often sinuous, ridges deposited by running water flowing off, or beneath, the glaciers. In plan they resemble a river drainage system, with tributaries converging downstream. The materials are primarily well-rounded gravels with sand, with the finer fractions of clay and silt washed out.

Eskers are probably the most obvious manifestations of gravel deposition in Ireland, by virtue of standing out in the landscape – where the concrete makers have not yet carted them away! But as aquifers they are not very favourable, and not only because of their obvious attractions as commercial sources of aggregate. For one thing, their limited extent means that they receive limited amounts of recharge. For another, their elevation (generally 10 – 30 metres) means that they generally have a deep unsaturated zone, and the gravel may not extend deep enough below the water table to be worth developing.

However, in some places it is possible to drill successful boreholes along the flanks of eskers where they are sufficiently broad. Eskers may also help to indicate less obvious deposits of gravel in the vicinity.

MORAINES

Moraines represent material dumped by glaciers at their margins or in retreat. They are usually composed of a variety of sediment types, which can include substantial amounts of sand and gravel sized material, but these deposits are usually poorly sorted and are not normally promising as aquifers. This was largely confirmed by some investigations in the late 1970s/early 1980s in the Galtrim Moraine of south County Meath (Minerex Ltd., 1983).

ALLUVIAL GRAVELS & RIVER TERRACES

These are a common location for gravel aquifer exploitation in Ireland, often by means of infiltration galleries. Alluvium can have a very varied texture, from silts to coarse gravels, and a borehole may encounter several thin layers of very different material.

Alluvial aquifers are often relatively narrow, perhaps extending only a few tens or hundreds of metres either side of a river or stream. At different times of year, groundwater may be moving from the river into the aquifer, or vice versa, depending on the relative elevations of the water table and the river.

One example is at Duagh, north Co. Kerry, where a 16 m deep borehole found gravels from 1.2 to 9 m below ground; the well yields about 340 m^3/d for a specific capacity of about 60 $m^3/d/m$.

RAISED BEACHES

These deposits are beach gravels formed at a time when the sea level was relatively higher than today. They tend to be very coarse and well-sorted, and have a very high permeability.

As far as I know, they have been developed only in Donegal, where quite shallow boreholes (12–16 m deep) have demonstrated specific capacities of over 200 $m^3/d/m$.

DUNES

These are not commonly developed in Ireland, to my knowledge, but they have been developed for fairly small developments in a few places, e.g. near Brittas Bay, Co. Wicklow. Strictly speaking, these aquifers will be of sand-size, rather than gravel-size, material, and probably very well-sorted (virtually single-size) sand, which means that well construction needs particular care. In this situation, well-points may be the best solution (see below).

POCKETS IN THE IRREGULAR SURFACE OF KARST LIMESTONES

The irregular bedrock surface of karstified limestones can be filled in by a variety of deposits, some of which can be sands and gravels of sufficient extent and thickness to be significant aquifers on a local scale.

The best example is perhaps a pocket of gravels which was successfully developed over thirty years ago near Ardfert, Co. Kerry, where a borehole (18.4 m deep) yields over 2000 m^3/d for a specific capacity of the same order. A gravel layer 9 m thick is overlain by a similar thickness of stiff till. Two other boreholes were drilled in the same area: about 400 m northeast, the main sand/gravel aquifer was less than 6 m thick, and another borehole only 17 m from the main supply well found 9 m of till directly overlying limestone bedrock!

Another example is at Ballykilliane in the South Wexford limestone area, where tests yielded over 2000 m^3/d from a borehole 19.6 m deep.

GRAVEL AQUIFER EXPLORATION

The exploration for, and identification of gravel aquifers in Ireland normally involves some or all of the following:

- Geological mapping, including examination of available maps of Quaternary deposits and rock outcrops
- Examination of aerial photographs
- Compilation of water well and geotechnical records and depth-to-bedrock information
- Review of available information on soil types and soil parent materials
- Exploratory drilling
- Geophysical surveys, particularly electrical resistivity and VLF surveys

MEANS OF EXPLOITATION

Gravel aquifers can be, and are, exploited by a rather wide variety of means:

- Boreholes
- Dug wells
- Infiltration galleries
- Springs
- Well points
- Collector wells

BOREHOLES

Bored wells in gravels require careful exploratory drilling, careful well design, construction, and development (Clark, 1981). All of this takes time and patience, so good wells in gravel aquifers cannot be constructed very quickly.

- An exploratory borehole is usually required, to establish the depths and types of deposits, and to provide samples for grain size analyses.
- From the well log and grain size analyses, an appropriate well design can be drawn up.
- It may be possible to convert the exploration well into a production well, or it may be preferred to drill a new production well close to the exploration well.
- Well construction needs careful supervision, to ensure that the final installation of casing and screen takes account of any changes in the strata encountered in the production well as compared with the exploration well.
- Well development and testing are extremely important and also need careful supervision.

A discussion of how to drill and construct wells in gravel aquifers could easily take up an entire paper. However, the principles and techniques are well covered in several modern textbooks. Most hydrogeologists depend on the book published by the Johnson Wellscreens company (Driscoll, 1986).

Bored wells can cope with thick or deep aquifers, and if properly constructed should provide the best sanitary protection.

DUG WELLS

Dug wells are the traditional means of exploiting shallow gravel aquifers, and are still much used in developing countries, where some very wide examples can be found. Large-diameter dug wells can produce very high yields.

In more developed countries they have largely been largely superseded by boreholes, partly because they are rather labour-intensive in construction.

They are suitable only for a shallow water table with a small annual fluctuation, and therefore for the more vulnerable gravel aquifers.

An advantage in developing countries is the ease of access, which allows mechanical repairs to be made without needing a drilling rig or crane, and the possibility of inserting several pumps, each serving a different user.

A concomitant drawback is that it is all too easy for the water in the well to be contaminated by livestock, vermin, or leaking pumps.

INFILTRATION GALLERIES

An Infiltration Gallery normally comprises a length of porous pipe in a shallow buried trench below the water table in the aquifer, draining towards a sump from which the water is pumped for use.

Galleries have been used for many years by local authorities to abstract water from alluvial or terrace gravels close to river channels. Engineers traditionally regarded them as a means of abstracting filtered water from the nearby river, i.e. as surface water sources.

In practice, the relative proportions of river water and groundwater abstracted will depend on several factors: the distance from the river, the relative elevations of river and water table, the permeability of the aquifer and of the sediments on the river bed, and the pumping rate. In many cases, much of the water abstracted is probably true groundwater, but the river is usually an important source of recharge, either by lateral flow or by periodic flooding (Daly, E.P. 1988, 1989).

Examples are known in Co. Cork, Co. Clare, Co. Kildare, Co. Kilkenny, and Co. Wicklow (Misstear, 1999; Wardick, 2000).

Galleries are only suitable where the water table is near surface and has a small annual fluctuation.

Galleries need to be carefully protected from contaminants, e.g. from slurry or fertiliser spreading. The quality of the river water should be taken into account when assessing the requirements for protecting a specific gallery from contamination.

SPRINGS

Springs usually represent natural groundwater outflow, although some springs have been artificially created through excavation.

Springs are vulnerable to contamination at outlet, especially where, for instance, grazing livestock have direct access to the water. However, for abstraction purposes, springs are usually impounded or contained in some way. They need careful protection.

Spring yields are subject to wide natural fluctuations, although impoundment usually mitigates this. It is often difficult to measure the actual yield and to predict maximum sustainable yield. A major reason for this is that the outflow of most springs is not measured in any way.

WELL POINTS

Well points are shallow, small-diameter screened wells, normally either bored or driven into the aquifer, and usually linked to a common suction pump. The slot size in the wellscreen is often small, to prevent entry of sand.

They are suitable only where the water table is close to the ground surface. They are good for shallow, thin aquifers, and particularly for finer gravels or sands.

- Example 1: Inish Oirr, where 3 shallow (up to 2.6m) well points were installed in blown sand, abstracting up to 59 m^3/d (Daly, E.P. 1987).
- Example 2: Ardanairy, Co. Wicklow, where a series of well points were designed to supply a golf course with 227 m^3/d of water from dune sands (K.T. Cullen & Co. Ltd. 1990).

COLLECTOR WELLS

A Collector Well is a concept which, as far as I know, hasn't yet been used in Ireland, but might well be used in the future. It is particularly applicable to highly permeable thin aquifers at shallow depth. Essentially it comprises a series of infiltration galleries or pipes driven outwards from a central sump or collector into which the galleries drain. It is thus particularly suitable for alluvial or terrace gravels, from which very large quantities can be abstracted. One patented design is known as the Ranney Well.

ADVANTAGES AND DRAWBACKS OF GRAVEL AQUIFERS

GROUNDWATER VULNERABILITY

Gravels are, more or less by definition, highly permeable. Therefore, chemical contaminants can penetrate relatively rapidly and, by GSI criteria for groundwater vulnerability, the aquifer will normally be highly or extremely vulnerable. The commonest exceptions to this are the buried valley aquifers, which may be covered by significant thicknesses of less permeable strata.

However, because flow in gravels is intergranular, the aquifer has good filtration properties, which will normally remove most microbial contaminants.

SOURCE PROTECTION AREAS

The high permeability and effective porosity of gravel aquifers, often allied to a low groundwater gradient, ensure that actual groundwater flow velocities are generally low, so that the Inner Source Protection Area (defined by the estimated 100-day travel time to the well) is normally quite small.

GROUNDWATER QUALITY

The hydrochemistry of gravel aquifers presents few problems unless there are complicating factors, e.g. peat deposits, or infiltration from a polluted river.

The high degree of filtration which is intrinsic to a gravel aquifer helps to give a high degree of protection from microbial contaminants.

RECHARGE AND STORAGE

Recharge to gravel aquifers is normally relatively high, owing to high infiltration capacity at surface.

High effective porosity and storativity usually ensure a dependable supply even from quite small aquifers.

PRESSURES

Gravel aquifers are often at low elevations and are often built on, or lie down-gradient from potential contamination sources.

Soils on gravel aquifers often good for tillage.

Old gravel pits have traditionally been used as convenient places for both legal and illegal dumping of wastes.

Thin gravel aquifers can be very sensitive to induced changes in water level, e.g. induced by large-scale drainage schemes.

TWO CASE STUDIES

TALLAGHT GROUNDWATER SCHEME, CO. DUBLIN

Dublin County Council had a short-term need for water in the Tallaght area and enquired about the prospects for groundwater in the vicinity. A local factory borehole had been successful and had confirmed the general geological indications that bedrock was generally absent in the area and some kind of gravel-filled buried valley might exist.

Four exploratory shell-and-auger boreholes were sunk by in 1978, about 400 metres apart along a north-south line across the most likely axis of the trough (see section). The two central boreholes (2 & 3) wore the most promising, with substantial gravel layers met at depth, and the trough was proved to have a depth of over 40 metres below surface. Short pumping tests were carried out, using a temporary well screen, and these confirmed that the aquifers were well worth exploiting. Particle size analyses showed the gravels to be coarse and poorly sorted,, and thus capable of 'natural development'. Production well yields of 1440-2160 m^3/d (13,000-20,000 gph) for BH-2 and over 2400 m^3/h (22,000 gph) for BH 3 were predicted.

Two production wells, 18 inches in diameter and equipped with 12 inch diam. plastic well screens, were drilled in 1979 by Groundwater Development Ltd of Mallow, and were tested at rates of 1968 m^3/d (18,000 gph) (BH 2A) and 2784 m^3/d (25,500 gph) (BH 3A). The wells were then equipped with pumps and soon were brought into service to cope with water shortages in the spring of 1980.

The wells were phased out a couple of years later when additional supplies from Poulaphuca became available. The wells had a problem of excessive manganese concentration.

I.D.A. INDUSTRIAL ESTATE, CARRIGTWOHILL. CO. CORK

This is one of the sites around Cork Harbour where the IDA has encouraged industrialisation. Surface gravel deposits occur extensively in this area, and the existence of a gravel aquifer at depth had been known for sometime from boreholes at a nearby factory. The IDA site was investigated in 1977 by the drilling of 7 exploratory shell-and-auger boreholes to depths of 21-46 metres below surface. The sediments were found to be very varied, but in general tended to be finer above and coarser below. The first four holes had trouble with very fine, salty, running sands, but finally the fourth hole found a coarse gravel aquifer between 34 and 41 metres deep. In BH 5 the deep gravel was only 4 metres thick but BH 6 found an excellent gravel between 14 and 34 metres deep. A later borehole for GSI hit bedrock at about 58 m below ground.

Two production wells were later sunk to depths of 40m and 44m, each with 8 m of Johnson wellscreen. Tested yields were 1090 m^3/d (10,000 gph) and 545 m^3/d (5000 gph). The water quality is good, despite increasing industrialisation on the site.

These two examples had a number of features in common:

- Favourable indications from previous boreholes and geological evidence that a gravel aquifer over 20m deep could exist in a buried valley.
- Careful exploratory boring, with emphasis on good sampling.
- Careful analysis of short pumping tests.
- Varied geological succession.
- Final successful development with large-diameter wells and wellscreens.

WHY ARE GRAVEL AQUIFERS IGNORED OR NEGLECTED IN IRELAND?

There may be a number of possible answers to this question. At the (considerable) risk of over-simplification, my analysis is as follows:

- Well drillers tend to ignore them because they don't fit in with their normal style of working, i.e. to complete a well very quickly at low cost and move on to the next site. Also, the type of drilling rig used by most well drillers is best suited to drilling in hard rock rather than in gravel or sand.
- Engineers tend to ignore them because they expect a groundwater source to be drilled quickly and cheaply; wells in gravel are more expensive than rock wells, and require more design and supervision. Also, gravel aquifers may be suspected of being more susceptible to pollution.
- Hydrogeologists tend to ignore them because they can't get well drillers or engineers interested! Perhaps there is also a lack of confidence in being able to deliver a successful, efficient well.

Wells in gravel are quite different from wells in rock, and the exploration and development of gravel aquifers is quite different from what is needed for rock aquifers:

- All rock aquifers – in Ireland, anyway – have very patchy permeability: you may drill a good trial well in one place, drill another a few metres away and get a very different yield, because you have missed the main water-bearing fissures. But well construction is relatively straightforward, provided the well doesn't collapse. So in rock aquifers the focus is often more on where to drill, and perhaps how deep, rather than on the aquifer geometry and the well design.
- With gravel aquifers, however, the position is almost reversed: once you have established the aquifer geometry, the actual location of the well is less important (although there may still be a lot of variability in the strata) but proper well design is crucial.

THE FUTURE OF GRAVEL AQUIFERS IN IRELAND

In some ways it might be said that little has changed in the last twenty years. Gravel aquifers continue to be undervalued in Ireland. Despite the fact that Johnson Wellscreens, a premier world manufacturer of wire-wound wellscreens, has a major presence here, there is still considerable ignorance of how to design, construct and develop a screened well in gravels. Almost every week I see records of wells drilled through gravel deposits in which the entire gravel aquifer is shut out by steel or plastic casing.

What *has* changed in the past twenty years? For one thing, we have a better idea of where gravel aquifers occur in Ireland. This is partly due to the county groundwater protection schemes which GSI has been undertaking over the past decade, and partly because hydrogeologists and engineers have carried out quite a bit of work in gravels over the same period – not as much as I would like to see, but still a fair amount (e.g. Gillespie, 1984; Shine, 1996).

I would like to suggest a few things we need to improve in relation to gravel aquifers in Ireland – which I hope this seminar may go some way towards bringing about:

- Awareness of their existence
- Appreciation of their value
- Willingness to invest in their development
- Commitment to their protection
- Skill, patience and confidence to design and construct efficient wells

I hope that our Groundwater Protection Schemes, combined with the forthcoming River Basin Management projects (initiated on foot of the EU Water Framework Directive), will help to further these aims.

REFERENCES

Clark, L. 1981. *Drilling & Sampling Gravel Aquifers.* Proceedings 1st Annual IAH Groundwater Seminar, Portlaoise.

Creighton, J.R. 1981. *Occurrence of Gravel Aquifers in Ireland.* Proceedings 1st Annual IAH Groundwater Seminar, Portlaoise.

Daly, E.P. 1987. Inish Oirr: *An appraisal of the effect of a proposed fish farming development on the public water source.* GSI Internal Report.

Daly, E.P. 1988. *Infiltration Galleries, Part 1.* GSI Groundwater Newsletter, No. 10, 4-5.

Daly, E.P. 1989. *Infiltration Galleries, Part 2.* GSI Groundwater Newsletter, No. 11, 3-4.

Driscoll, Fletcher G. 1986. Groundwater and Wells, 2nd Edition. Johnson Filtration Systems Inc., St. Paul, Minnesota.

Gillespie, D. 1984. *Cooley Groundwater Supply Scheme.* Proceedings 4h Annual IAH Groundwater Seminar, Portlaoise.

K.T. Cullen & Co. Ltd. 1990. *Water Supply to Proposed Golf Course at Ardanairy, Co. Wicklow.* Unpublished report.

Minerex Ltd. 1983. *The Hydrogeology of Co. Meath: A Preliminary Assessment of Groundwater Potential.* Report to Meath County Council.

Misstear, B.D.R. 1999. *Groundwater & Surface Water: Exploiting a Combined Resource.* Proceedings 19th Annual IAH Groundwater Seminar, Portlaoise.

Ó Súilleabháin, Cormac, 2000. *Assessing the Boundary between High and Moderately Permeable Subsoils.* Unpublished MSc dissertation, University of Dublin, Dept of Civil, Structural and Environmental Engineering.

Shine, Cecil, 1996. Case History: *Gravel Aquifer Investigations in the Glen Swift Valley, Letterkenny, Co. Donegal.* Proceedings 16th Annual IAH Groundwater Seminar, Portlaoise.

Tipperary (SR) County Council/GSI/FÁS, 1998. *Site Suitability Assessments for On-Site Wastewater Management.* Tipperary (SR) County Council, Geological Survey of Ireland & FÁS.

Wardick, Michael, 2000. *Infiltration Galleries.* Unpublished Senior Sophister dissertation, Dept. of Civil, Structural & Environmental Engineering, Trinity College Dublin.

Wright, G.R. 1988. *Aquifers of the Future: (1) The Mid-Kildare Gravels.* Proceedings 8th Annual IAH Groundwater Seminar, Portlaoise.

This paper is published by permission of Dr Peadar McArdle, Director, Geological Survey of Ireland.

2. *Keynote Paper:* International Perspectives on Gravel Exploitation

Charles Jones, Principal Hydrogeologist, Mott MacDonald, Cambridge, UK.

INTERNATIONAL PERSPECTIVES ON GRAVEL EXPLOITATION

Charles Jones,

Principal Hydrogeologist, Mott MacDonald, Demeter House, Station Road, Cambridge CB1 2RS, UK

ABSTRACT

International experience of the exploitation of gravel aquifers indicates their general importance in many parts of the world and the large variety of issues encountered in their development. Heterogeneity and proximity to the surface are key characteristics that influence the exploitation of groundwater in gravel aquifers. Case histories from the countries south of the Himalayas and from Scotland demonstrate issues of sustainability, the choice of development technology, interaction with river flows, water chemistry and aquifer biology.

INTRODUCTION

International experience of the exploitation of gravel aquifers for groundwater supply appears to reflect closely the themes of this conference. As with any other type of aquifer, the topics of investigation, development and protection appear in iterative cycles as scientific and engineering techniques and methods are refined and new challenges are identified and overcome. Are there aspects of hydrogeology that are unique to gravel aquifers or do they form part of a continuum from bedrock aquifers to the finest sands ands silt? Inevitably, erosion follows orogeny and gravels will usually turn up somewhere nearby in subsequent deposition. However, being high-energy deposits the first feature that will be encountered in most investigations will be lateral and vertical **heterogeneity**. The other frequent, but not universal feature, is their **proximity** to the land surface.

Before launching further into the subject it is perhaps as well to reflect on a Taoist precept quoted by Marshall McLuhan – "It is not the clay pot that is useful but the void within". In most gravel aquifers, large, open, well-connected voids are much more important than the gravel matrix material (unless this has an economic significance of its own). Drury (1972) describes how, using a scale to compress over $2*10^9$ years for the evolution of the earth into a week, the development of sands and gravels would last around 2 minutes and the timebase of the hydrologic cycle would last around $4 * 10^{-4}$ seconds compared to a human lifespan of $9*10^{-3}$ seconds. The renewal and purity of groundwaters in gravel aquifers usually reflect a time base measured in days or years- the gravel matrix appears very static in comparison.

The importance of gravel aquifers for water supply in many parts of the world should not be underestimated. In a summary from a major review of unconsolidated sedimentary aquifers (UNSAs), funded under the ODA/BGS technology and Research Programme, Cullen et al (1996) include a statement showing how superficial sands and gravels may not show on geological maps at the global or country scale but only at 1:200,000 did important rivurine sand and gravels or 'dambos' appear. BGS conclude *"Unconsolidated sediments , and therefore UNSAs, are ubiquitous"*. We should conclude that gravel aquifers must be quite common for this reason.

Walton (1970) states "..*probably more than 90 percent of all groundwater pumped in the conterminous United States comes from sand and gravel....grouped as watercourses, abandoned or buried valleys, plains and intermontane valleys*" and the last category "*yields more than half of all water pumped*". He concluded that groundwater's place in the US economy is more important than appears from the statistic that it constitutes only a fifth or sixth of all water withdrawals.

Gleick (1998), in a review of the world's freshwater resources, estimates that in 1995, groundwater contributed 105 km^3/a of 469 km^3/a total freshwater withdrawal in the US and that groundwater withdrawals had doubled since 1950. Worldwide, freshwater use is projected to be 4000 km^3 in 2000.

In Asia, outwash from the Himalayas has produced sand and gravel aquifers stretching from Balochistan in western Pakistan eastwards through the northern states of India, the Terai of southern Nepal to Bangladesh in the west. North of the Himalayas, infill of the Aral and Tarim basins spans from Turkmenistan through Kazkhastan and Uzbekistan into China. Possibly half a billion people in those areas depend on the interaction of rainfall, runoff and unconsolidated aquifers for their drinking water and agricultural water supplies.

In contrast, in the arid highlands of Iran and the southern Gulf states, isolated oasis communities have developed that are (or were) wholly dependent on ancient systems of *kareze/quanat/aflag* to provide gravity fed water supplies through gravel aquifers.

In other continents, and especially in Europe, the statistics are more difficult to overview so simply. Even so, the same themes of reliability, availability and feasibility occur repeatedly as described in the following case histories.

CASE HISTORY 1 – EXAMPLES OF GRAVEL AQUIFERS SOUTH OF THE HIMALAYAS

The gravel aquifers south of the Himalayas have been classified in many ways:

- recharged from rainfall or recharged from surface water
- pumped by surface mounted centrifugal pumps (often referred to as shallow tubewells or STW) or by deep set submersible pumps (often referred to as deep tubewells or DTW)
- pumped for irrigation or for domestic use or for agricultural drainage
- driven by electricity or diesel

These distinctions arise from a number of concerns such as how the resource is calculated or the extent to which the abstraction leads to return flows to groundwater or rivers or increased consumptive use through evapotranspiration. At first, the technological factors may seem remote from hydrogeology. However to the nations concerned there are underlying issues about equity and accessibility of supply, and the role of owner-operators that are fundamental to their rural economies.

Nepal

The Terai area of southern Nepal extends in a belt 0 to 50 km wide between the Curia Range and the Indian border at altitudes of 76 to 280 m above sea level. The Terai is underlain by over 500 m thickness of outwash sands and gravels of rivers debouching from the Siwaliks and main Himalayan range. Near to the mountain front, in the 'Bhabar Zone' the sediments are very coarse and boulders and cobbles present major difficulties to local drillers using manual low cost methods of well construction. However, permeability can be very high and a 3 or 6 m screen is sometimes used to supply 6 to 15 l/s STW pumps. In these few areas where water levels are shallow enough, 100-150 mm casing and screen is driven in (the 'thukwa' method) to refusal and so steel pipes with crude slots are standard. The majority of the Terai is further from the mountains, water levels are often shallower and cobbles are less frequent and indigenous methods of shell and augur drilling or jetting are used to set a variety of casing and screen types. Average STW discharge is higher at 11 l/s but up to 30% discharge less than 10 l/s.

The use of groundwater was as follows:

Type	**Water use**	**Irrigation**		**Water supply**	
		(Mm^3/a)	(%)	(Mm^3/a)	(%)
Groundwater	410	380	24	25	74
Surface water	1210	1203	76	9	26
Total	1620	1583	100	34	100

Source: UN (1989)

A 1996 survey carried out for the Government of Nepal and the Asian Development Bank covering the central and eastern regions of the Terai concluded that STW were feasible over an area of 5350 km^2 or 61% of the cultivated area. Since there were reported to be around 28,000 STW, the average density of STW was only 5 /km^2 whereas 15 to 30 /km^2 would be needed to provide full irrigation coverage depending on the levels of conjunctive use in the 2220 km^2 also served by surface water irrigation.

It was concluded that the main obstacles to groundwater use were neither lack of recharge from the 900-1800 mm of dry –year rainfall nor excessive water level fluctuation in the gravel aquifer over the winter period of high consumptive use. Instead, a combination of social, economic and institutional factors were restraining groundwater development. These factors included risk-aversion towards the occasional low yield wells, the capital and energy costs of pumping, the small and fragmented land holdings giving rise to a need to share water and responsibility against a background of lack ofcapital and collateral amongst the rural poor.

Recommendations included a technical component to improve the tubewell 'product' and achieve lower running costs and greater reliability.

Bangladesh

Flat alluvial plains underlie most of the country. With rainfall on the plains varying from around 1900 mm/a to 3500 mm/a and 1234 km^3 of river flow pouring into the country to add to the 123 km^3 of surface runoff it is perhaps surprising that the 15 to 120m of sand and gravel in the top 100-1000m of sediments is exploited for groundwater. Nevertheless, there are heavy demands as a result of the long winter dry season when wheat is grown extensively, and the need to provide supplementary irrigation before the monsoon rice crop. In 1989 there were an estimated 160,000 STW, 24,000 DTW and 900,00 handpumps.

The use of the total groundwater resource of 15,000 Mm^3/a was as follows:

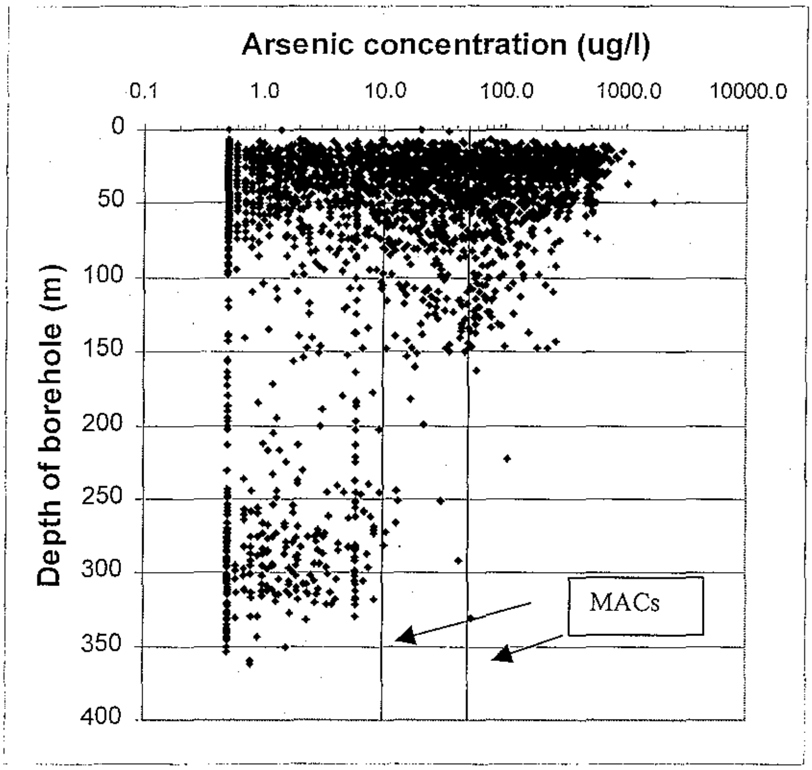
Type	Water	
	(Mm^3/a)	(%)
Total used	10,000	100
Irrigation use	9000	90
Municipal	400	4
Industrial	400	4
Domestic	100	1

Source: UN (1989)

The growth in numbers of STWs was dramatic during the 1980s and 1990s as the local industries geared up to providing cheap plastic casing and screens and pumps and diesel engines. Gleick reports that by 1995, total water use (including surface water) in Bangladesh had risen to 22.5 km^3 of which agricultural use was 96%.

In the last 5-10 years there have rising concerns about the levels of arsenic in drinking water derived from pumped groundwater.

Arsenic data from Bangaldesh aquifers



Although the obvious result from over 3500 samples is that concentrations reduce with depth, an underlying issue is that a great deal of effort was spent investigating and developing the shallow aquifer layers for irrigation. For this use, the deepest aquifer layers would be uneconomic and different water quality issues than potability standards were investigated.

Other investigations by BGS for the UNSA studies have concentrated on the nature of the sedimentary structures within the sand and gravel aquifers. Identification of channel, meander and floodplain deposits etc within the borehole profile was undertaken in conjunction with measurement of inflow profiles along screens, laboratory research into screen entry losses, review of gravel pack designs and tests to measure the 'ageing' or loss of specific capacity with time.

Uttar Pradesh, India

The vast gangetic plains of Uttar Pradesh lie south of the Terai and the sand and gravel aquifers are extensively developed for irrigation. Shankar (1992) describes how the irrigated area doubled from 5.3 million hectares (mha) in 1950 to 12.8 mha in 1986. In the same period, the area fed from groundwater rose from 41% to 50% of the total. Interestingly, Shankar's field studies into the socio-economics of groundwater irrigation can arrive at very useful conclusions about water sharing and purchase amongst the rural poor and the impact of electricity subsidies whilst concentrating on the 'visible measurables' such as hours, hectares and equipment ratings. Difficult to measure parameters such as discharge, percolation losses and evapotranspiration use are not brought into the presentation.

The key groundwater issue in the state is achieving a level of use that increases agricultural production and rural incomes, reduces waterlogging and related risk of salinisation but without permitting over-development of the resource and falling water tables. In common with the states of Haryana, Punjab and Rajasthan, a water balance method developed by the central groundwater development board is applied to a series of 'blocks' within each district of the state. As the calculated groundwater consumption passes through development thresholds, each block can be downgraded from 'white' – development permitted (and subsidy available through the agricultural credit system), through 'grey' to 'black' – no development (and no subsidies). Since the rainfall declines from over 1500 mm/a in the monsoon rice growing areas of the east towards Patna in the neighbouring state of Bihar, to less than 750 mm towards Dehli and Haryana, there are an increasing proportion of grey and black blocks in the west.

Another issue has been the reclamation of tracts of sodic soils that have been abandoned by farmers and the possibility that the sodicity has resulted from centuries of surface water irrigation or capillary rise from shallow fluctuating watertables.

Punjab and Sindh, Pakistan

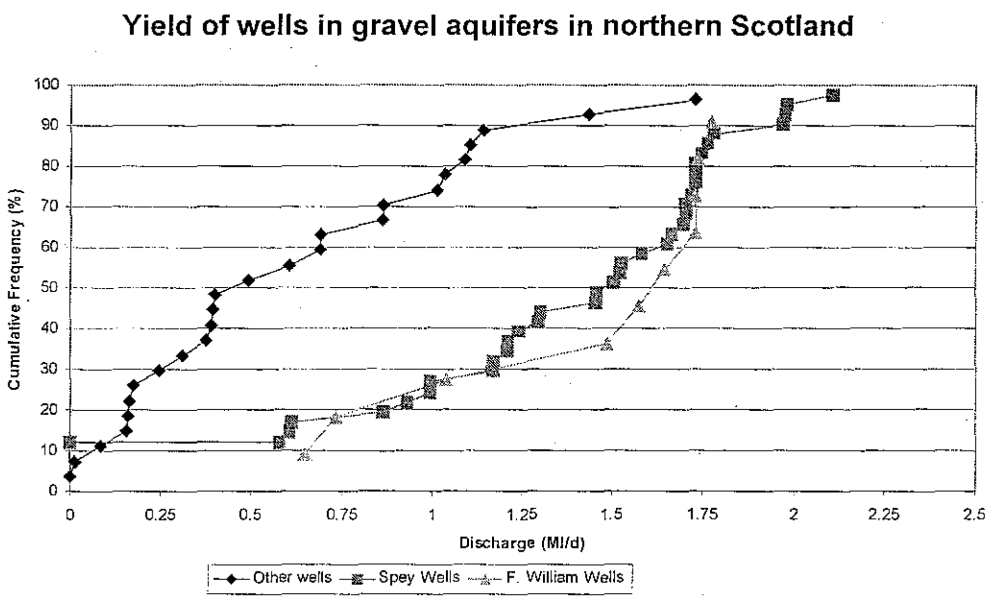
Nazir Ahmad (1974) describes how the Indus plains of Pakistan cover some 37,000 km^{2}and, from one set of estimates for the period before 1970, 40 km^3 percolated to groundwater of which less than 20% derived directly from rivers and the remainder from the 98 km^3 of surface water diverted into canals. As a result, the watertable in the shallow aquifers rose to within the rooting depth of the cotton crop and the twin perils of waterlogging and salinity became a cause of great concern. By the 1990's there were reports of falling water levels in parts of Punjab as had also been observed in the adjacent states in India. The huge increase in groundwater use had come about as farmers exploited this 'new' groundwater resource and achieved a form of conjunctive use across the basin. Jones et al (1997) suggested that the feasibility of lining existing canals to reduce seepage losses could be severely reduced where losses were recovered by farmers in such a way as to maximise use of groundwater storage, facilitate better timeliness of irrigation and reduce inequity of distribution between head and tail users in a canal command.

Many parts of Sindh suffer from the added problem of ancient saline water at depths less than around 60 m. Studies suggested that this is the critical limit for freshwater lens thickness to be developed sustainably. As a result, a series of projects have been implemented to improve irrigation and drainage by pumping out saline water for ultimate disposal into the Arabian Sea. The Left Bank Outfall Drain Stage 1 Project provides drainage to around 0.5 mha in lower Sindh through a combination of more than 1500 drainage wells and some areas of horizontal drainage. As presented in Lee et al (1988), these drainage measures are necessary to allow the land resource to accept the enhanced irrigation supplies to be delivered under the Project. Although well-sorted fine sand aquifers dominate, there are also some coarser gravel layers at depth. As described in Shearer and van Wonderen (1992), the issue of the relative importance of these as a source of saline inflow was studied as part of the pilot study into the design of scavenger wells where computer modelling had to take density and mixing effects into account.

CASE HISTORY 2– GRAVEL AQUIFERS IN NORTH SCOTLAND

In their review of alluvial and glacial aquifers in the North of Scotland Water Authority (NoSWA) area, Jones and Singleton (2001) discuss 12 groundwater schemes of which two are based on infiltration galleries. The main driver for such schemes is the fact that surface runoff in the region can be excessively coloured and turbid and surface water treatment costs can be high. In contrast, groundwater has little colour or suspended solids and has a more stable water quality. Treatment needs may be minimal. Groundwater quality varies greatly both between and within wellfields and testing and sampling are always required during the investigation and construction phases. Studies in the mid-1980's for the Spey scheme (Watt *et al.* 1987) pointed to the significant role of residence time and temperature in colour removal by natural bacteria.

The fluvio-glacial and alluvial aquifers have been investigated or developed at a number of sites, Robins and Ball (1987), Ball (1997). Site investigation can be used to improve success rates, and can be based on a combination of geomorphology, trial pitting test boring or surface geophysics. Jones and Singleton (2001) present results from major projects such as the 27 Ml/d Spey and 10 Ml/d Fort William schemes to the 0.16 Ml/d supply for Dalwhinnie. It is demonstrated that useful yields of up to 2 Ml/d can be achieved from dug wells or drilled boreholes even where the aquifer thickness is limited but well yields can be very variable even within one wellfield. Flow logging and step testing have shown that some of this variability is due to the level and thickness of the main gravel aquifer zone.



Inflow rates are 2.85 Ml/d and 3.39 Ml/d at the infiltration galleries at Ordiequish (on the opposite bank of the River Spey to the Spey wellfield and the Wrack (on the River Deveron). The latter gallery was constructed as a Ranney well (Anon 1961). The average inflow rates are 9 m^3/d per m length and 27 m^3/d per m length and compare with another gallery in river gravel in Cardiff which the author has studied previously where the infiltration rate is 8.2 m^3/d per m length.

The use of 0.75 m or larger diameter perforated concrete pipes laid in a trench is common for major galleries. The cost of this type of construction rises dramatically with depth if this is beyond the reach of an excavator, and with increased depth below the watertable. Low discharge private schemes, may comprise a few lengths of 75 mm or 100 mm agricultural field drain feeding to a collector chamber.

In contrast to a multiple borehole scheme, there is less collector pipework and valving and so pumps, power supply and control equipment are less complex an infiltration gallery but local variations in water quality cannot be managed so easily.

Neither bankside wells nor an infiltration gallery are used to increase the recoverable water resource by mobilising aquifer storage. Monitoring shows a close link between river and groundwater level changes and the groundwater scheme is treated as if it merely abstracts river water.

REVIEW AND CONCLUSIONS

This paper has highlighted a number of schemes from around the world because, together, they demonstrate the vital importance of gravel aquifers in many countries. Each example has introduced at least one water resources management or development issue. Socio-economics, choice and transferability of available technology and hydrogeological understanding, recharge, interception or interference with river flows, scale of development, horizontal or vertical sources for abstraction, water chemistry and aquifer biology have all had an impact on at least one of the cases presented. There are many others, as for example anthropogenic pollution, that remain. It is the author's hope therefore, that as the conference progresses, these themes will be seen to be relevant to many of the other presentations and will provoke some healthy debate and discussions that may assist hydrogeologists in Ireland in the future.

The author would also like firstly to stress that the views expressed are his own and secondly to extend his sincerest thanks to the organisers for their kind invitation to present this paper.

REFERENCES

Anon (1961) "Ranney collector for the Lower Deveron Water Board", Water and Water Engineering, January 1961.

Ball D, (1997), "The North West Highlands: the potential of groundwater at selected sites for rural water supply", Technical Report WD/97/42, British Geological Survey

Cullen RJ, Parsons SB and Calow RC (1996), " Unconsolidated Sedimentary Aquifers Review N0.9 – Irrigation", British Geological Survey Technical Report WC/96/9.

Drury S, (1972), "Resources and Environment", in Understanding the Earth, Open University Press

Gleick PHJ, (1998), "The World's Water – The Biennial Report on Freshwater Resources", Island Press, Washington DC

Lee PS, Shaikha and Youssef (1988), "Left Bank Outfall Drain, Integrated Irrigation and Drainage in Pakistan", ICID 13th Congress Special Session R7.

Jones CRC and Singelton AJ (2001). "Public water supplies from alluvial and glacial deposits in northern Scotland", in Groundwater in the Celtic Regions, eds Robins NS and Misstear BRD, Geologial Society London, Special Publication **182**

Jones CRC, Haigh M and Davey CJ (1996) " Unlined Canals – the Grateful Earth" ICID special symposium on canal lining, Lahore.

Nazir Ahmad (1970), " Ground Water Resources of Pakistan", Ripon Printing, Lahore

Robins, NS & Ball, DF (1987), "Groundwater in the superficial deposits of Scotland - a review". Applied Research and Development Report Number ARD, Scottish Development Department.

Shankar K (1992), "Dynamics of Ground Water Irrigation", Segment Books, New Delhi

Shearer TR and van Wonderen JJ (1992), "Scavenger Wells 4-Simulation Modelling", Proc 12th SWIM, Barcelona.

WaltonWC (1970), "Groundwater Resource Evaluation", McGraw-Hill

Watt GD, Mellanby JF, van Wonderen JJ. & Burley M (1987), "Groundwater investigations in the lower Spey valley, near Fochabers", Journal of the Institution of Water & Environmental Management, **1**, 89-103.

3. Production Well Operation in Gravel

Kees van Beek, Senior Geohydrochemist, Netherlands
Waterworks Testing and Research Institute.

PRODUCTION WELL OPERATION IN GRAVEL

C.G.E.M. (Kees) van Beek
KIWA Water Research
P.O. Box 1072, 3430 BB Nieuwegein, The Netherlands.

The operation of a production well depends on the condition of the well at commissioning, the applied abstraction regime and the local geological and chemical conditions at the well field. Operation of the well is an important item. At commissioning the well should meet set standards and conditions, the last of which can be checked by geophysical methods. An ill designed and/or constructed well obviously needs more maintenance than a perfect well.
The maintenance of a well depends also on the abstraction regime. Important items are the abstracted flow rate in relation to the geohydrological conditions and the frequency of (submersible) pump operation.
A real danger of each well(field) is clogging.Clogging is defined as the decrease in specific capacity of the well in time. There are several types of clogging; in phreatic gravel aquifers the most prevalent type will be the accumulation of iron hydroxides and/or manganese oxides in the screen slots. With this type of clogging, if the clogged wells are rehabilitated in time, the capacity can be brought back to the value at commissioning. As clogging is a characteristic of the local conditions at the well field, immediately after rehabilitation the well will start clogging again.

INTRODUCTION

The operation of a production well depends on the interplay of:
1. The state of the well at commissioning. This state is governed by the well design and by the well construction.
2. The abstraction regime of the well. Relevant factors are the applied capacity and the frequency of switching on and off the (submersible) pump.
3. The actual state of the well. The actual state determines the maintenance necessary to keep the well in a reliable condition.

Realize that if a well is not in a reliable condition, the well will surprise you at periods of greater demand, that means during a period you need the water the most!

THE STATE OF THE WELL AT COMMISSIONING

The state of the well at commissioning is governed by the well design and by the well construction. For well design there are several handbooks, for instance Bieske and Bieske (1973), Driscoll (1986), DVGW (1996), Kiwa (2000) and NGWA(1996). These handbooks, and Howsam et al. (1995), present also much information about monitoring and rehabilitation.
The design-capacity of a well is governed by the groundwater velocity at the well bore wall. In the Netherlands often the Sichardt velocity is used or a draw down of two meters.
Numerous papers have been published about this normative velocity at the well bore wall, but this is still one of the less well understood parts of the well design. If groundwater consists of distilled water, and the soil matrix and gravel pack consist of uniform glass beads in its most dense packing, it is impossible to set part of the soil matrix or the gravel pack in motion, and the groundwater velocity at the borehole wall may be infinite. This means it is not the velocity itself that is normative, but some underlying factor. This underlying factor has probably to do with the presence of colloid sized particles in the abstracted groundwater (van Beek et al., 1999)
The construction of the well is for a great part a matter of confidence between the client and the drilling company. There are no general standards to judge the state of a newly drilled well. As a criterion often the absence of sand in the abstracted water is used (what is absence?), or the obtaining of the design capacity of the well. However, there are geophysical methods to check whether clay

barriers are put in the right place and it is also possible to check whether voids in the gravel pack are absent. The construction of the well itself may be checked with the help of CCTV.
When problems are expected, or when it concerns a new well field, it is advised to record the original inflow to the well with the help of a flow measurement, i.e. the inflow as a function of depth over the screen. In future, the result of this measurement can always be used as a reference. This is especially helpful if clogging occurs at the bore hole wall.

ABSTRACTION REGIME OF A PRODUCTION WELL.

The normative capacity of a well is the capacity the well can easily meet, and this is often met by experience. In the Netherlands there are well fields that are operated with a draw down of 2 m that have problems, and there are well fields that are operated with a draw down of 5 m, that have no problems. An important aspect in the normative capacity is the mutual distance of the wells: this distance should be so large that the wells do not influence each other too much.
Another point is the operating frequency of the (submersible) pump; it is generally considered that the more smooth the wells are operated the better. This is not to hard to imagine: each time a (submersible) pump is switched on, the whole well, and surrounding gravel pack and aquifer are stressed. Moreover if more than one groundwater quality is abstracted by one well, mixing of these different qualities is favoured by frequent switching on and off.

MAINTENANCE OF A WELL

The main point of maintenance of a well is guarding its capacity, as its capacity is threatened by clogging. Clogging of a well is characterized by a gradual decrease of the specific capacity of the well over time. The specific capacity is here defined as the abstraction (m^3/h) over the draw down (m). The draw down is the difference in water level in the well during abstraction and at rest.
It is possible to distinguish between two types of clogging:

1. clogging of the well screen, and
2. clogging of the bore hole wall.

The type of clogging is easily distinguished with the help of an observation pipe in the gravel pack. If the screen of the observation pipe is located at some depth of the screen of the production well, there is in the case of clogging of the well screen during abstraction a great difference in water level in the production well and in the observation pipe. In the case of clogging of the bore hole wall there is during abstraction hardly any difference in water level between the production well and the observation well. The difference between both types is explained in figure 1.

Clogging of a well is a very annoying phenomenon. If you are unaware of its presence, it will surprise you on the day you need the water the most, i.e. on the day of the greatest demand. If the well is equipped with a submersible pump, depending on the characteristics of the pump, you will hardly notice any decrease in production during clogging, until the waterlevel in the well during production reaches the pump intake and the pump starts sucking air.
In order not to be surprised by the phenomenon of clogging, the well(field) needs monitoring of the specific capacity.

MONITORING

Before a well is put into service the well is developed, that means the drilling mud and other material is removed from the bore hole wall. At that time the value of the specific capacity is also measured. And this value is the reference point for the future behaviour of the well. Sometimes the value of the specific capacity increases after the well has been taken into service. The value of the specific capacity can only increase if the well has not been developed completely. If this is the case, the maximum value reached will be used as the reference value.
In order to monitor the state of the well, the specific capacity needs to be measured regularly. The frequency depends on the information available of the well field (i.e. is it a new well field, or is there already available a long history of the well field), on the variability of the results of the measurements and on the frequency of rehabilitation.

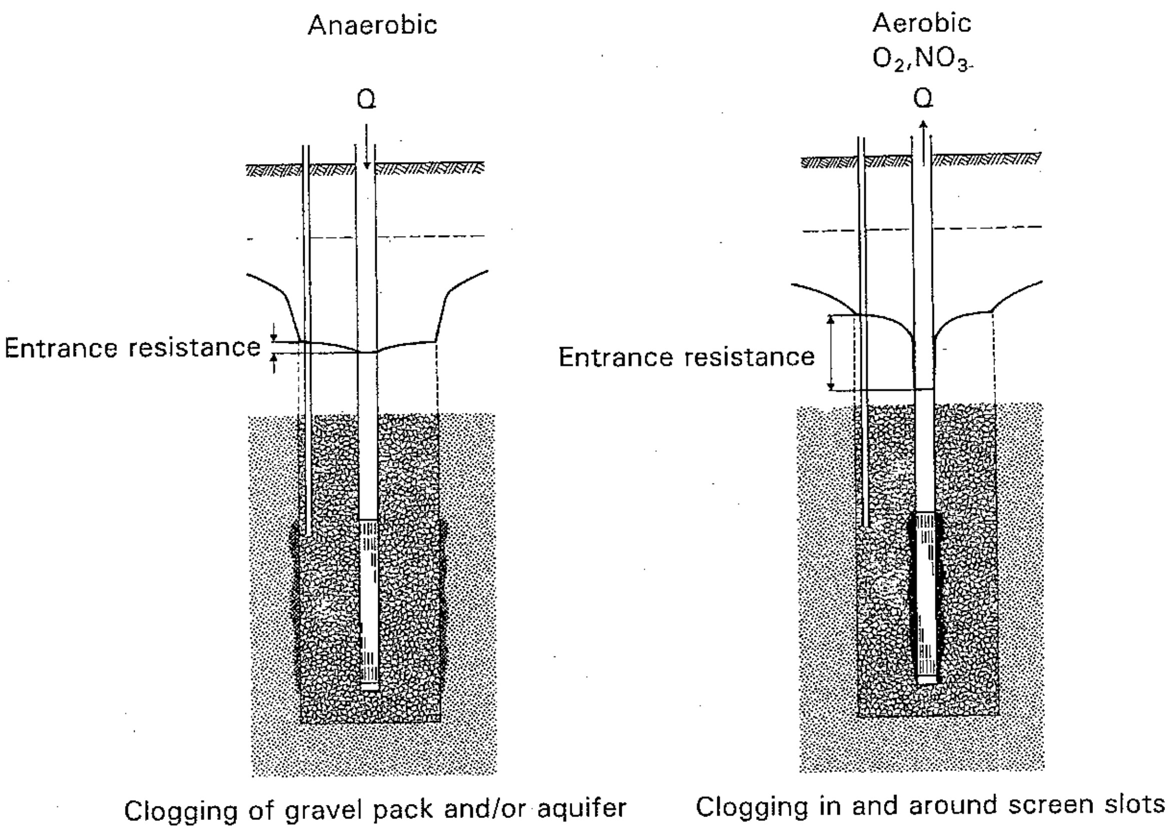


Figure 1: Distinction between clogging of the borehole wall and clogging of the screen slots. Clogging of the screen slots is characterized by a large entrance resistance, while it is absent at clogging of the borehole wall.

During monitoring it is not necessary to measure the exact value of the specific capacity. As the most important goal of the monitoring is to see whether clogging is occurring or progressing, the only requirement of these measurements is that the results are mutually comparable over time. This means that the measurements should be performed in an identical way over time, i.e. with the same wells on and off and after the same time of waiting when the pump is switched on or off.

CAUSES OF CLOGGING

The two types of clogging are caused by two different classes of causes. When it is apparent that clogging is occurring, and the well is equipped with an observation pipe in the gravel pack, it is possible to distinguish immediately between these two types, see figure 1.
Clogging of the screen slots is caused by mixing of incompatible watertypes, i.e. on mixing of these watertypes precipitates are formed. In that situation the chemical composition of groundwater is not homogeneous with depth. As an example, figure 2 shows the distribution of the concentration of nitrate, iron and aluminum with depth. From this figure it is clear that the groundwater in the upper part of the aquifer contains aluminum and nitrate (and oxygen) and in the lower part iron (and manganese).

Under these conditions a well will abstract different watertypes, which are very well separated in the aquifer, but which start mixing the first moment of encounter, i.e. in the screen slots of the well. When iron containing water mixes with oxygen containing water, precipitates of iron hydroxides will develop:

$4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3(s) + 8H^+$ (± biomass)

And the same holds for manganese:

$2Mn^{2+} + O_2 + 2H_2O \rightarrow 2MnO_2(s) + 4H^+$ (± biomass)

These last two processes may be mediated microbially, e.g. by Gallionella and Lepthotrix spp. In that case a mixture of biomass and precipitate arises, which is very effective in clogging wells.
There is also a process that forms only biomass, i.e. by mixing of methane containing groundwater with oxygen containing groundwater:

$CH_4 + 2O_2 \rightarrow CO_2 + H_2O$ + biomass

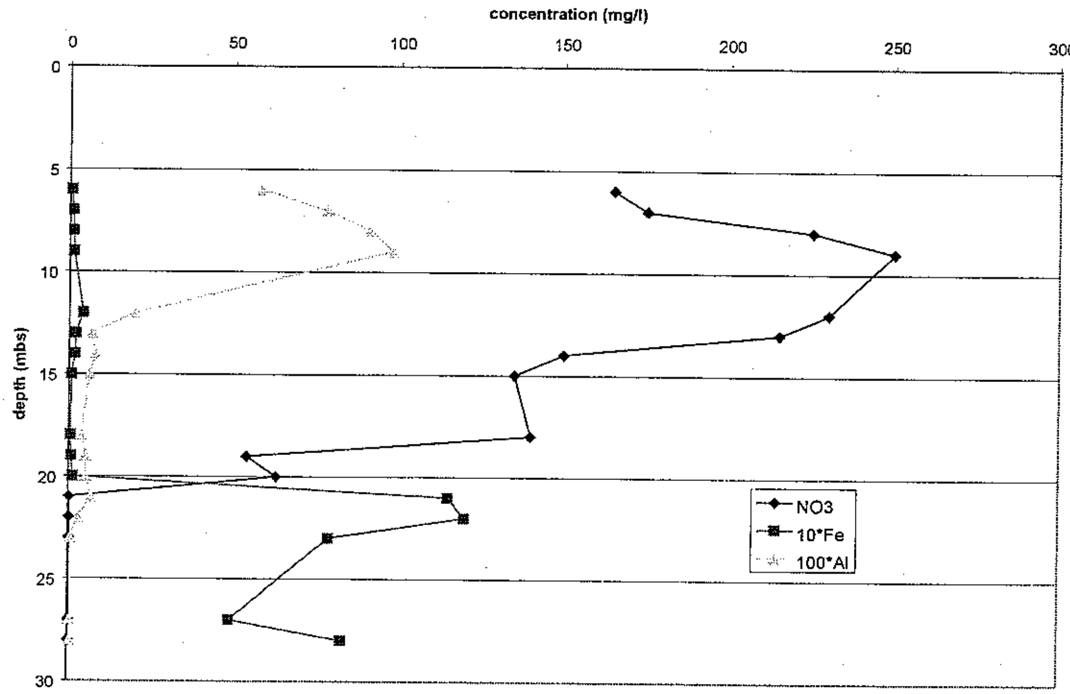


Figure 2: Concentration profiles of nitrate, iron and aluminum in miniscreenwell NP40 in Vierlingsbeek. If the screen of a production well is positioned between 10 and 30 m below surface, nitrate (and oxygen) containing water will mix with iron containing water, and acid aluminum containing water will mix with more alkaline aluminum free water. In this case the well will clogg by precipitates of aluminum hydroxides as well as of iron hydroxides (and manganese oxides).

Recently another type of clogging precipitate has been recognized. Due to anthropogenic acid deposition high concentrations of aluminum have developed in shallow groundwater. When this (acid) aluminum containing water mixes with deeper more alkaline water precipitates of aluminum hydroxides will be formed:

$Al^{3+} + 3H_2O \rightarrow Al(OH)_3(s) + 3H^+$

This type of clogging will only occur if the pH of the groundwater has a value lower than about 4,5.

There is one more process that may lead to the formation of precipitates: mixing of two types of groundwater both unsaturated with respect to calcite, where the mixed water becomes saturated with respect to calcite:

$Ca^{2+} + HCO_3^- \rightarrow CaCO_3(s) + H^+$

Besides the presence of an entrance resistance, the presence of this type of clogging is confirmed by the presence of deposits on the submersible pump and in the terrain pipes. Except for the calcite case, a geohydrochemical reconnaissance study will provide enough information on whether there is a danger for clogging of the screenslots or not.

Clogging of the bore hole wall occurs by accumulation of migrating colloid sized particles on that wall. In the past this type was ascribed to a combination of the development of sulfate reducing bacteria and the formation of precipitates of iron sulfides whether or not in combination with particles (van Beek and van der Kooij, 1982). As a number of cases have emerged where sulfate reduction is absent and there is still clogging, at present this type is ascribed to accumulation of colloid sized particles (van Beek et al., 1999). This type of clogging is much less understood than clogging of the screen slots.

In the Netherlands about 2/3 of the well fields experience well clogging. The type of clogging is about equally divided between the screen slots and the bore hole wall. The clogging of the screen slots is mainly caused by accumulation of precipitates of iron and manganese, whether or not in combination with biomass. Clogging by precipitates of calcite has not been reported in the Netherlands, however it is reported in Germany (Niehues, 1999).

REHABILITATION

When the monitoring of a well indicates that clogging is occurring, the well needs to be rehabilitated. It is advised to rehabilitate a well at the latest before the specific capacity has decreased to 50% of its value at commissioning, and preferably before 60 to 70%. Moreover it is advised not to wait too long because:

1. in the presence of biomass, beneath this biomass very reducing conditions develop, which could give rise to the presence of all kinds of secondary processes and the formation of secondary precipitates,
2. during ageing precipitates of iron and manganese may harden, and may be harder to remove due to this hardening, and
3. when a well is completely clogged, a good mixing of chemical with the clogging material becomes impossible. This holds in particular for the clogging of the bore hole wall: the regenerant cannot come into close contact with the clogging material, but flows around it.

Wells with clogged screen slots are easy to rehabilitate, as the clogging material is easy accessible for exerted forces or added chemicals. Available methods include:

1. mechanical methods, like brushing, surging and jetting. As these methods are most friendly for the environment, it is advised always to start with one of them. Freezing, heating, blasting and ultrasonic methods may also included in this category,
2. chemical methods. During the formation of all precipitates acid (protons) are produced. So reversing the reaction by adding acid, will dissolve the precipitates. The most common acid applied is hydrochloric acid.
   The formation of iron hydroxides and manganese oxides is an oxidation reaction. This process may be reversed by adding a reducing agent. This is a new development (Houben et al., 2000). When biomass or manganese is the main clogging agent, the use of an oxidant may be useful. The most common oxidant used is hydrogen peroxide (be careful by applying this chemical, as it may decompose instantaneously, giving rise to a geyser .i.e. pressurised hot water).

With the rehabilitation of this type of clogging some remarks have to be made:

1. There are many rehabilitation methods and many chemicals for rehabilitation available on the market. Each method or chemical has its own merits depending on the conditions of the well field. As the owner of the well field knows these conditions the best, he should make his choice depending on these conditions. If he is not sure of the situation, there is room for an independent advisor. Money spent on the wrong method is lost money.
2. However one precipitate may dominate the process, the clogging is usually caused by a mixture of precipitates. As each method preferentially removes some precipitates, it is advisable to regularly change methods.
3. In the field not only the screen slots are clogged, but also the first 1 or 2 cm around the well. Although there is theoretically no explanation for the presence of precipitates outside the well, it probably has to do with the switching on or off of the pump, or with the flowing of groundwater

when the well is at rest, when differences in potential are present. Be sure to remove also this part.

4. A well is fully rehabilitated when its capacity after the treatment is equal to the capacity at commissioning. A relative improvement (we have obtained values of 1000% improvement) is no measure for success. If the well is not completely rehabilitated, the wrong method has applied, or the correct method has been applied in the wrong way.

Clogging of the bore hole wall is difficult to reach, and wells, which show this type of clogging, are for that reason difficult to rehabilitate. We have had some success with sodium hypochlorite, but this is a very unfriendly chemical for the environment. Sometimes the capacity after rehabilitation is greater than before. This is only possible if the well has not been completely developed before commissioning. This also puts the attention on an alternative explanation of the rehabilitation success: which part of the improvement is due to removal of the clogging material and which part is due to the late development of the well.
For well fields sensitive to this type of clogging, it is advised to remove the mud completely, that means to develop wells completely and not to the designed capacity.
Figure 3 shows as an example the history of the draw down of both types of clogging.

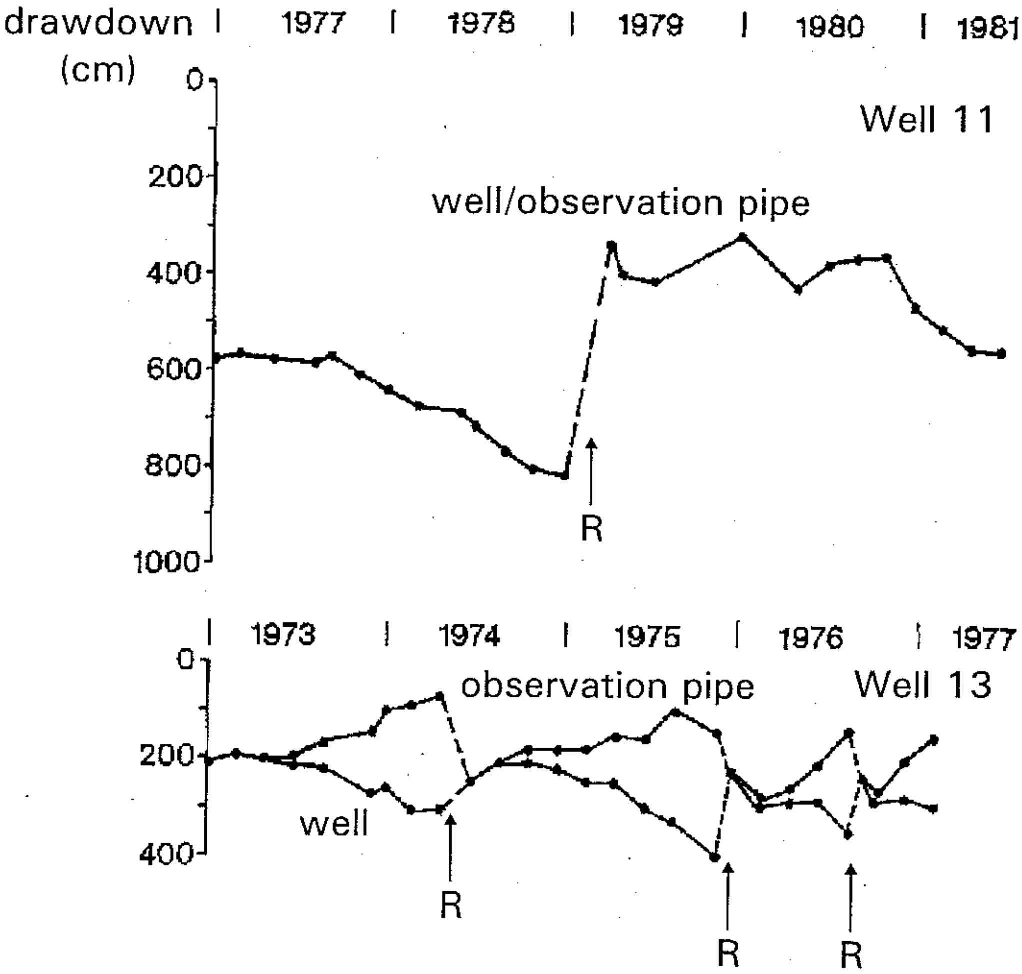


Figure 3: Examples of the history of the draw down of clogging of the bore hole wall (upper part) and of the screenslots (lower part), and the results of rehabilitation (R).

PREVENTION

If well clogging occurs on a well field, complete prevention is hardly possible, but mitigation is possible.
Mitigation of clogging by mixing of two incompatible watertypes is possible by removing one of the two reactants. There are several ways to remove one of the two reactants:

1. Installation of separate wells with shallow screens and other wells with deep screens. In this case the shallow screens abstracts (mainly) the oxygen containing water and the deep screen (mainly) the iron- and/or manganese containing water.
2. Application of in situ iron removal. By this method oxygen is periodically injected into the aquifer, after which during a longer period iron-free water can be abstracted. The same method may be applied for the removal of manganese, but this process appears much harder.
3. Removal of oxygen. On this moment there are experiments for the in situ removal of nitrate in the soil. Comparable methods may be used for the removal of oxygen.

As already mentioned mitigation of clogging of the bore hole wall is possible by complete removal of the mud cake. Moreover continuously producing wells clog slower than wells which are frequently switched on and off. (Moser, 1979). The more constant a well is producing the less mixing is occurring and the least amount of fines is set in motion.

COST OF MONITORING AND MAINTENANCE

From the foregoing it is clear that the occurrence of clogging is an intrinsic property of the well field. Replacing a clogged well by a new one does not solve the problem, as the new well will also start to clog immediately. Often it takes more time before a new well needs its first rehabilitation then when it has already been rehabilitated once or more, i.e. the first rehabilitation interval is often longer than the subsequent ones. In the Netherlands the cost of rehabilitation amounts on an average to 10 to 15% of the cost of a new well. This means that only in the case where the first rehalibilitation interval is 7 to 10 times longer than the subsequent ones, is it advantageous to sink a new well in stead of rehabilitation, but this situation will hardly ever occur.

LITERATURE

van Beek, C.G.E.M., E.J. Schrama, M.W.J. Eck, J.A.M. van Hoof and J.J.P. Verstraelen (1999): Clogging of deep wells by colloids, H_2O 32 (16/17) 21-24 (in Dutch).

van Beek, C.G.E.M. and D. van der Kooij (1982): Sulfate-reducing bacteria in ground water from clogging and nonclogging shallow wells in the Netherlands river region, Ground Water 20 (3) 298-302.

Bieske, E. und E. Bieske (1973): Production wells, 6 ed., 389 p, R. Oldenburg Verlag, München, Vienna (in German).

Driscoll, F.G. (1986): Groundwater and wells, Johnson Division, St. Paul, Minnesota, 2° ed., 1089 p.

DVGW (1996): Handbook Drinking Watersupply, Volume 1, Waterabstraction and Watermanagement, Oldenburg Verlag, München (in German).

Houben, G., Chr. Schroeder und Chr. Treskatis (2000): Experiences with rehabilitation of wells with the help of a newly developed pH-neutral rehabilitation chemical, BBR 51 (12) 42-47 (in German).

Howsam, P., B. Misstear and C. Jones (1995): Monitoring, Maintenance and Rehabilitation of Water Supply Boreholes, CIRIA 137, London.

Kiwa (2000): Document Well(fields), Design, Construction and Operation of production wells, Kiwa-BTO 2000-110C, Nieuwegein (in Dutch).

Moser, H. (1979): The clogging of vertical screen wells, the technical and economical aspects, explained by example of the well field of the waterwork Mannheim-Käfertal, DVGW Schriftenreihe 201, 385-418, DVGW Eschborn (in German).

NGWA (1998): Manual of Water Well Construction Practices, National Ground Water Association, 2° Ed.

Niehues, B. (1999): DVGW-Survey "Well rehabilitation", Informationsveranstaltung, 2. Friedrichshafener Brunnenbautage, DVGW Berufsbildung, p 173-185, DVGW, Bonn (in German).

4. Geophysical Methods for the Investigation of Gravel Aquifers

Peter O'Connor, PGeo, APEX Geoservices Ltd., 4 Sandyford Office Park, Dublin 18.

GEOPHYSICAL METHODS FOR THE INVESTIGATION OF GRAVEL AQUIFERS.

Peter O' Connor PGeo, APEX Geoservices Ltd., 4 Sandyford Office Park, Dublin 18.

ABSTRACT

Geophysical surveying has not been widely used in Ireland as part of groundwater investigation programs but work elsewhere has involved a range of applications to both regional and local scale exploration of the water resources and the vulnerability of gravel aquifers. Electrical and electromagnetic methods are the most commonly used and the physical properties they measure are closely related to water content, soil composition and the presence of any contamination. Geophysical methods are relatively inexpensive and non-invasive and it has been shown that hydrogeological properties such as permeability and transmissivity can be reliably estimated from the measured geophysical data if suitable calibration information from boreholes is available. Surveying techniques have evolved rapidly over the last 5-10 years with the development of multi-electrode, multi-channel computer controlled systems capable of acquisition and quality control of high resolution data sets. High speed surveying methods using either land-based or airborne towed systems with on board GPS are now widely used and enhanced processing and interpretation software capable of interfacing with CAD/GIS is available. Borehole geophysical techniques provide a rapid quantitative record of borehole lithology and physical properties.

INTRODUCTION

Some geophysical methods, such as resistivity surveying, have been regularly used in groundwater work whereas other methods such as induced polarisation and electrokinetics are still at the experimental stage. The traditional application of geophysical methods has been in the exploration and delineation of aquifers, usually prior to drilling and testing. The most common methods used in the exploration of gravel aquifers have been the electrical resistivity and electromagnetic methods (MacDonald et al, 2000; Geonics, 1995; Daly, 1994) mainly due to the relationship between water content and electrical properties, and their relative low cost and ease of use.

Seismic refraction and reflection have been applied in selected investigations where further information is required on bedrock profiles and sediment stratigraphy respectively (Bradford et al., 1998). Ground Probing Radar (GPR) can be applied effectively under certain ground conditions and provides high resolution information on shallow (c. 10m) sand and gravel deposits (Cardimona, 1998).

Gravity surveys are limited to objectives such as mapping sediment filled bedrock channels but have been used on an experimental basis to monitor aquifer depletion. Magnetic profiling can be useful in outlining water bearing deposits where the sediment fill is derived from igneous or metamorphic bedrock. More recent innovations are methods such as electrokinetics (Reynolds, 1997) and proton magnetic resonance. Induced polarisation has been used recently to provide specific information on clay content for vulnerabilty assessment (Slater et al., 2000).

Geophysical borehole logging is an established procedure in most large scale hydrogeological investigations and provides a quantitative record of lithological variations and related hydrogeological properties to augment the observational data, with a wide array of measurements now possible. Crosshole resistivity tomography has been recently used as an aid to focused packer testing.

The oil exploration industry has long recognised the value of geophysical methods for reservoir characterisation and recovery estimation (Worthington, 2000). Derivation of hydrogeological parameters such as permeablity and transmissivity from geophysical data are discussed in Frolich and Kelly,1995; Hiegold et al, 1979 and MacDonald, 1999.

PHYSICAL PROPERTIES

POROSITY

The relationship between bulk soil conductivity (the inverse of resistivity), soil porosity and pore fluid conductivity is based on a form of Archies Law (Archie, 1942). This states that:

$$\sigma_a = \sigma_w \Phi^m s^k + \sigma_{clay}$$

where

σ_a	=	bulk conductivity of the soil (S/m)
σ_w	=	conductivity of the pore fluid (S/m)
σ_{clay}	=	clay component (S/m)
Φ	=	soil porosity (fractional)
m	=	constant which varies with particle shape (1.2 - 1.9, Jackson et al 1978)
s	=	fraction of pore volume filled
k	=	constant(~ 2.0).

The constant m varies with particle shape ranging from 1.2 for spherical to 1.9 for platy fragments. The factor for clay content will depend on the amount and type of clay minerals present in the soil. Pore fluid conductivity will vary with the degree of ionic concentration or total dissolved solids (TDS) present and will also vary with temperature. Using the above equation it is possible to demonstrate basic variations in resistivity or conductivity with porosity, pore fluid conductivity and the degree of saturation (Fig 1A - 1C). Porosities of mixed sand and gravel are in the range 20-35% (Fetter, 1994) and a value of 30% has been used for Figs 1B & 1C.

Fig 1A shows the variation of resistivity with porosity and the shape factor. Fig 1B shows the response to an increase in the pore fluid conductivity such as would occur due to contamination of the groundwater. This is expressed in more easily measurable conductivity units which show a linear increase. Fig 1C, which has a log scale, illustrates the rapid decrease in resistivity which occurs as the gravel becomes saturated. These modelled values are in line with observed values of these parameters for Irish Gravel deposits. Typical resistivity and seismic velocity values for Irish overburden deposits are summarised in Table 1.

Fig 1A. Variation of bulk resistivity of saturated soil with porosity

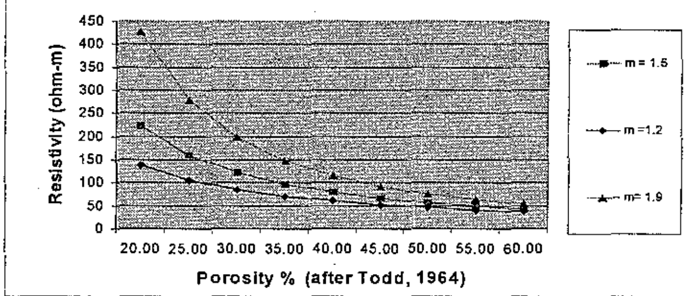


Fig 1B. Variation of bulk conductivity of saturated soil with pore fluid conductivity (30% porosity)

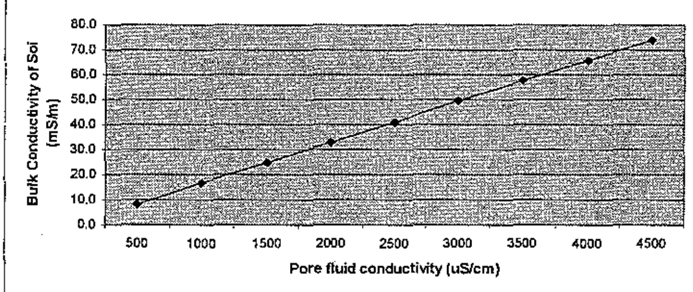


Fig 1C. Variation of bulk resistivity with degree of saturation (30% porosity)

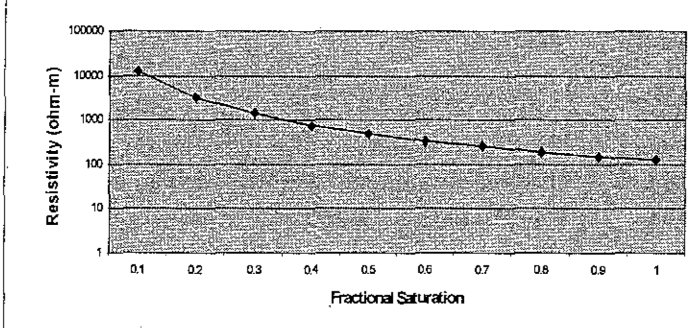


Table 1. Observed geophysical properties of Irish overburden deposits

	Resistivity (ohm-m)	Conductivity (mS/m)	P-velocity (metres/s)
Clay	20-30	33-50	
Silty clay	30-50	20-33	
Silty gravelly clay	50-100	10-20	1800-2200(stiff)
Gravelly clay	100-250	4-10	
Clayey gravel	250-500	2-4	
Gravel(unsaturated)	500-3000	0.3 - 2	300-1100
Gravel(saturated)	125-350	3.3-10	1500-1900
Gravel(contam/saline)	5 to 20	50-200	

PERMEABILITY AND TRANSMISSIVITY

Examples of derivation of aquifer properties from resistivity measurements are contained in MacDonald, 1999; Kalinski, 1993, Frolich & Kelly, 1995: Niwas & Singhal, 1981 and Heigold et al, 1979, among others. The theoretical basis for the relationship between permeability and resistivity is discussed and empirical relationships are calculated from observed and modelled data. In clay-free gravel aquifers permeability (K) and resistivity (ρ) have an inverse relationship:

$$K \alpha 1/\rho \quad \Rightarrow \quad K\rho = C_1 \qquad \text{where } C_1 \text{ is constant.}$$

If clay content is high, the amount of clay present is directly related to both resistivity and permeability and K and ρ have a direct relationship:

$$K \alpha \rho \quad \Rightarrow \quad K/\rho = C_2 \qquad \text{where } C_2 \text{ is constant.}$$

Heigold, 1979, used the inverse relationship to establish a correlation factor between resistivity and pump test data for water-bearing glacial outwash deposits in Illinois. The correlation factor was:

$$H = 386.40\ R_{rw}^{-0.93283}$$

where H = permeability in cm/sec
and R_{rw} = resistivity of the water saturated zone in ohm-cm.

Kelly, 1977, established a direct relationship between the resistivity and permeability of a glacial sand and gravel aquifer in New England (Fig 2) and also between the transverse resistance and transmissivity. The transverse resistance and its accompanying parameter, the longitudinal conductance, are used to deal with the problem of non-uniqueness in the interpretation of resistivity sounding curves and are known as the Dar-Zarouk parameters. They are calculated from the resistivity layer thickness (h) and layer resistivity (ρ) as follows:

Transverse resistance $R_T = h * \rho$
Longitudinal conductance $C_L = h / \rho$

and can be readily obtained during the processing of resistivity sounding data. The transverse resistance is the dominant factor when current flows across a high resistivity layer which is bounded by lower resistivity material. Longitudinal conductance occurs where current flows along a low resistivity layer bounded by higher resistivity material.

MacDonald, 1999, illustrates the analogy between Transmissivity (T) and electrical current flow and derives the following relationships:

$$T = R_T C_1$$

and $$T = C_L C_2.$$ where C_1 and C_2 are constants.

Correlation factors can therefore be established for coincident resistivity soundings at pumped wells and transmissivity values extrapolated across the aquifer using resistivity soundings. This approach, using transverse resistance data was successfully applied to the exploration of gravel aquifer basins by MacDonald, 1999 (Fig 3) and by Frolich and Kelly, 1985.

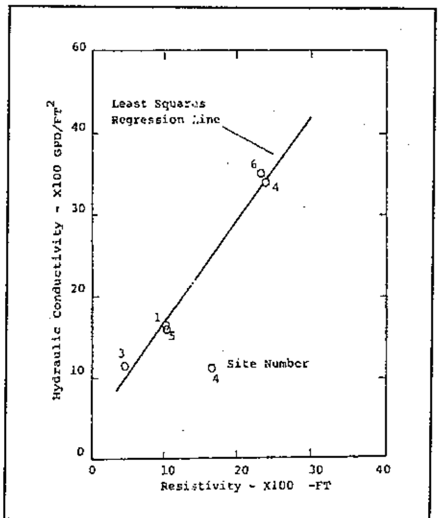


Fig.2 Aquifer resistivity vs permeability (Kelly 1977).

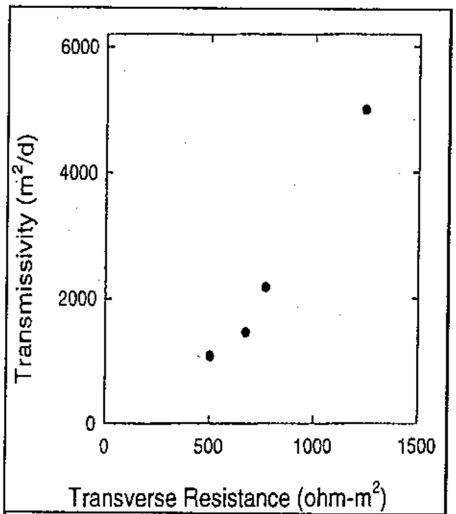


Fig.3 Transverse resistance vs transmissivity (MacDonald, 1999)

Kalinski (1993) outlines a procedure for obtaining time-of-travel (TOT) through surface protective layers by measurement of longitudinal conductance over a sand and sandstone aquifer in Nebraska. Detailed mapping of protective clay layers over gravel aquifers has been carried out by Aarhuus County Council in Denmark as part of a US$70m geophysical mapping program being carried out over a 10 year period (Sorensen & Sondergaard, 1999).

Laboratory or in-situ measurements of the conductivities of soil samples and mixtures can be made using methods similar to those described in BS1377: Part 6 or in Sternberg & Levitskya, 1998. These results can then be compared with Particle Size Distribution (PSD) analysis of the samples to provide correlation factors between conductivity/resistivity and soil composition.

Overall, published information on the derivation of hydrogeological parameters from geophysical (mainly resistivity) data shows that good results can be obtained if correlation factors for the particular geological setting are available and variables such as groundwater conductivity and anisotropy can be constrained. Direct measurements of permeability by in-situ and laboratory methods often show significant variation (Swartz, 2000) and in-situ falling head tests are considered of less value in regional vulnerability assessments due to their limited sample area. Permeability and transmissivity data obtained from resistivity measurements are by their nature large scale, bulk measurements and this together with their low cost (~ 130 euro per sounding), non-invasive nature, and the additional stratigraphic information they provide, indicates that they should be an essential part of any large scale hydrogeological mapping program.

GEOPHYSICAL TECHNIQUES AND RECENT DEVELOPMENTS.

This sections deals with the main geophysical methods used in gravel investigations and recent developments in equipment, surveying techniques and interpretation methods. Details of the theoretical basis of each method are not be included. For this text books, such as Reynolds, 1997, are recommended.

RESISTIVITY

Resistivity surveying measures the resistance of the ground to electrical current flow and traditional surveying methods have employed variations of the four-electrode array to measure either lateral or vertical variations in resistivity.

Constant Separation Profiling

Measurements of lateral variations use a moving array with a fixed electrode spacing to outline resistivity changes on a profile or grid. Common electrode spacings would be 10 or 20 m (5-10 m penetration) with readings on a 50 m or 100 m grid. This method is often used to outline gravel deposits which have a high resistivity in the upper unsaturated zone compared to silts and clays.

Depth Soundings

Vertical variations in resistivity are measured by keeping the array centred on one point and increasing the electrode spacing from 1 m to 64 or 128 m (32 - 64 m penetration). Common electrode configurations are the Wenner and Schlumberger arrays and the Offset Wenner method which uses the Barker Cable to improve productivity and data quality. Depth soundings are interpreted by computer curve matching to give the thickness and resistivity of the subsurface layers. The resolution of the method decreases with depth. Automated continuous recording of shallow depth soundings using a towed array is routinely carried out by Aarhus County Council during vulnerability mapping using the PACES technique (Sorensen, 1996). Continuous resistivity profiling and depth sounding can also be carried out using the recently developed Geometrics Ohm-Mapper system .

2D Resistivity Profiling

Over the last few years conventional Wenner or Schlumberger depth soundings have been largely replaced by 2D Resistivity methods. This involves use of a multi-electrode system with 32, 64 or 128 electrodes at 5 m or 10 m spacing such as the Campus Tigre or ABEM Lund system. The electrodes are connected to a resistivity meter via a multi-core cable and the resistivity measurements are taken using selected sets of electrodes to give high resolution coverage both laterally and vertically. The acquisition process is controlled by computer and the raw data is inverted using a least-squares modelling process.

An example of a 2D resistivity profile through the Curragh aquifer and its interpretation is shown in Fig. 4. A second example through the Nore Basin gravels is shown in Fig. 5. Both examples were recorded with a 64 electrode Campus Tigre system and show the transition from high resistivity to low resistivity at the watertable as well as variations within the saturated zone. Topographic corrections were not applied.

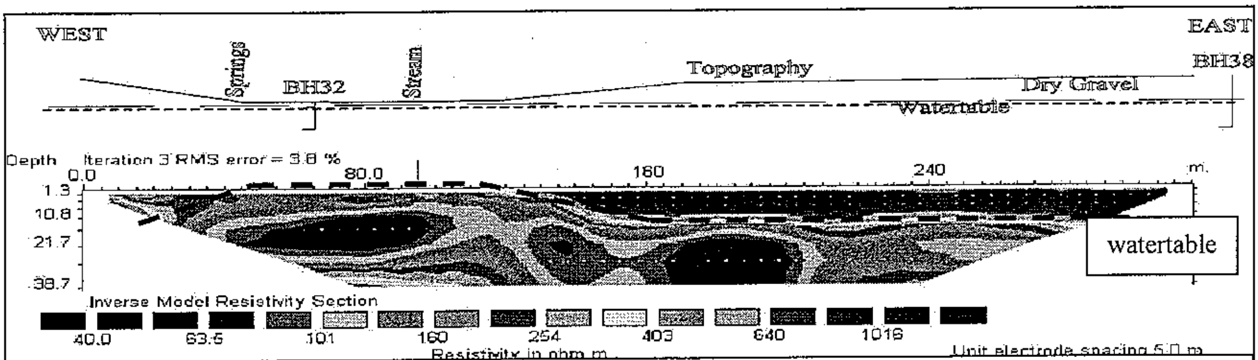


Figure 4. 2D Resistivity Profile over the Curragh gravel aquifer at Pollardstown, Co. Kildare.

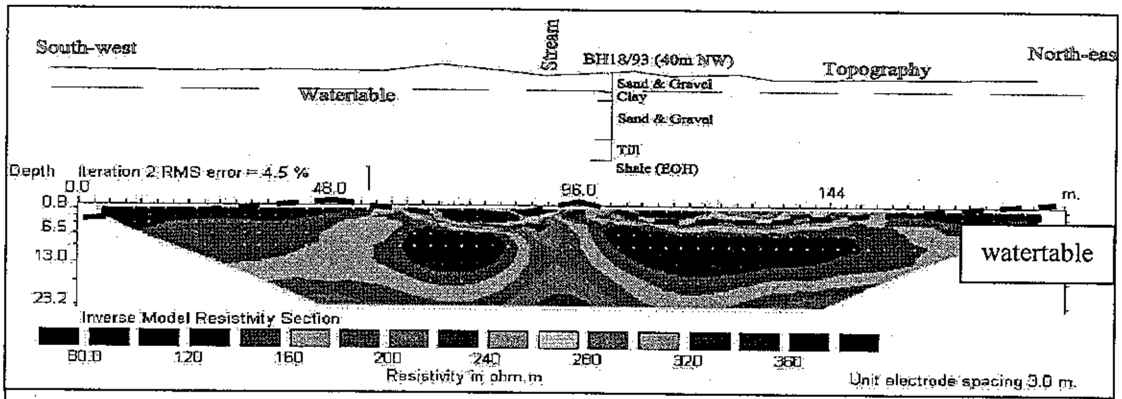


Figure 5. 2D Resistivity Profile over Nore Basin gravel aquifer at Oldtown, Co. Kilkenny.

Time lapse Resistivity

This so-called 4D method involves re-measurement of 2D resistivity profiles at fixed time intervals and monitoring the changes in ground resistivity with time (Pokar et al, 2001). Typical applications are viewing changes in resistivity and anisotropic effects associated with drawdown in pumping tests, infiltration of surface water or other liquid, and leachate monitoring under landfills using fixed electrode systems installed during construction.

ELECTROMAGNETICS

Frequency domain

These systems operate at typical frequency ranges of 0.4 to 10 kHz and involve measurement of the secondary currents induced in the subsurface by a primary field. The ratio of secondary to primary current is usually calibrated in units of ground conductivity (mS/m) on instruments such as the EM31/CM31 and the EM34. An advantage of these systems compared to resistivity methods is that they do not require current injection or ground contact and are consequently faster, however they do not have the resolution of direct current methods.

The EM31/CM31 conductivity meters are single operator instruments which have a depth range of 0 - 6m and are widely used for reconnaissance mapping of near surface sediments and also for mapping of shallow leachate plumes in porous sediments. Recent innovations include the incorporation of a GPS receiver and data logger which allows rapid acquisition either on foot or by vehicle. The EM34 and Max/Min instruments have a greater depth of penetration (10 - 40 m depending on intercoil separation and frequency) than the EM31, but require two operators and are slower to record.

Time Domain

Time domain methods transmit large moment primary electromagnetic fields into the ground using transmitter coils laid out on the ground surface and then measure the decay of the induced secondary field after the primary current is switched off. Good penetration can be achieved through medium or low resistivity sediments (up to 300 m) and the methods are especially suited to geological settings where there is a very low resistivity layer at the base of the aquifer.

Surveys are carried out using the Protem receiver or similar combined with the TEM-37, 47 or 57 transmitters depending on the depth of investigation. The PATEM system, developed by the University of Aarhus, consists of a high moment towed transmitter coil and receiver with on-board GPS which is used to map the Tertiary clays at the base of the sand and gravel aquifers that provide the groundwater resources for much of the county (Sorensen, 1995). This system allows individual TEM soundings to be recorded at intervals as low as 25m and has led to improved data quality and better recognition of noise and coupling effects.

VLF methods
VLF EM and Resistivity methods have a long history of use in Ireland, mainly for mineral exploration. These rely on the reception of electromagnetic radio waves (16- 20kHz) from military transmitters using instruments such as the EM16R. Due to their relatively low frequency, part of these waves travel through the top 25-50 m of the ground and can therefore be used to map ground structure. Their use in gravel exploration is limited due to their low vertical resolution but they can be used in resistivity mode to map the base of shallow aquifers and outline gravel bearing channels in bedrock.

Airborne Surveys
High resolution airborne EM surveys using helicopter mounted equipment such as Fugro's DIGHEM have recently been used to outline the extent of sand and gravel deposits on a regional scale as part of aquifer mapping projects (C. Murphy, pers comm.).

SEISMICS
Refraction
Seismic refraction surveying consists of measuring the traveltime of refracted seismic waves through the different subsurface layers. The wave source is usually a hammer, shotgun or weight drop and the received signals are recorded using geophones at 5 or 10 m intervals connected to a multi-channel (12 or 24) seismograph. In gravel exploration there is usually a good velocity contrast between the looser unsaturated material and the underlying saturated zone whose velocity is largely governed by the seismic velocity of water. Transmission of seismic waves though saturated sand and gravel material is good and a refraction from the bedrock can often be achieved. Refraction surveys can be useful for outlining gravel bearing channels in the bedrock to depths of 30 - 50 m..

Reflection
Reflection surveys using high frequency sources and receivers and close geophone spacings can give good resolution of aquifer stratigraphy and bedrock profile to depths of several hundred metres. Surveys using towed geophone strings and truck mounted vibratory sources along paved roads such as those employed by Ramboll in Denmark can be carried out for a cost of around euro 3,000/km (U. Nielsen, pers comm..).

GPR
Application of Ground Probing Radar methods to the investigation of gravel deposits in Ireland has yielded variable results and is highly dependent on the thickness of the clay cover and the aquifer electrical conductivity. Penetration depths of 5 - 10 m have been achieved in unsaturated gravels in the Irish midlands while depths of up to 30m have been reported from Canada. GPR can give excellent resolution of shallow gravel deposit stratigraphy.

BOREHOLE LOGGING
The established borehole geophysical logging techniques such as resistivity, SP and natural gamma have now been augmented by a wide range of additional methods. Case histories are presented in Buckley, 2000 and some Irish examples are given in Daly, 1994. Geophysical logging can contribute valuable information to any hydrogeological investigation program. Gamma and Electrical Conductivity logs have been used by Corona & Mavko, 1999 to predict clay content and porosity and estimate flow properties in shallow sand and gravel units in Ontario.

CONCLUSION
Geophysical methods are effective tools in the exploration of gravel deposits and can provide information on the extent, setting and stratigraphy of both small scale and regional scale deposits at relatively low cost and with minimal disturbance to the ground surface and landowners. Hydrogeological properties can be derived from the geophysical data once adequate calibration material is available.

ACKNOWLEDGEMENTS

The co-operation of KT Cullen and Company, and Eugene Daly Associates in providing borehole data and sites for 2D resistivity surveying is acknowledged. The permission of the Environmental Division of Aarhus County Council to use some of their published material in the presentation is also acknowledged. Mr Colm Murphy of Fugro Airborne Surveys and Mr Uffe Nielsen of Ramboll are thanked for their assistance.

REFERENCES

Archie, G.E., 1942, The electrical resistivity log as an aid to determining some reservoir characteristics. Trans. A.I.M.E. 146, 54-62.

Bradford. J.H., Sawyer, D.S., Zelt, C.A., & Oldow, J.S., 1998, Imaging a shallow aquifer in temperate glacial sediments using seismic reflection profiling with DMO processing: Geophysics, 63, 1248-1256.

Buckley, D.K,. 2000. Some case histories of geophysical downhole logging to examine borehole site and regional groundwater movement in Celtic regions. In: Groundwater in the Celtic Regions, Geol. Soc. Spec. Publn. 182, pp 219-237.

Cardimona, S.J., Kadinsky-Cade, K. & Clement, W.P., 1998. Seismic reflection and ground penetrating radar in a shallow aquifer: Geophysics 63, 1310-1317.

Corona, W.W. & Mavko, G. 1999. Predicting clay content and porosity from gamma ray and conductivity logs. Proc. SAGEEP 1999, 425-433.

Daly, E.P. 1994. Groundwater resources of the Nore river basin. Geol. Survey of Ireland Report Series RS 94/1.

Fetter, C.W., 1994. Applied Hydrogeology. Prentice Hall.

Frolich, R.K. & Kelly W.E., 1985. The relationship between hydraulic transmissivity and transverse resistance in a complicated aquifer of glacial outwash deposits. Journ. of Hydrology, 79: 215-229.

Geonics Ltd, 1995. Groundwater Exploration Applications, Selected Papers.

Heigold, P.C., Gilkeson, R.H. Cartwright, K. & Reed, P.C., 1979. Aquifer transmissivity from surficial electrical methods. Groundwater, 17(4):338-345.

Kalinski, R.J., Kelly, W.E., Bogardi, I. & Pesti G., 1993. Electrical resistivity measurements to estimate travel times through unsaturated ground water protective layers. Journ. of App. Geophysics, 30, 161-173.

MacDonald, A.M., Burleigh, J., & Burgess, W.G., 1999. Estimating transmissivity from resistivity soundings: an example from the Thames Gravels. QJEG, Vol 32, Pt 2. 199-206.

MacDonald, A.M., Ball, D.F., &McCann, D.F. 2000. Groundwater exploration rural Scotland using geophysical techniques. In: Groundwater in the Celtic Regions, Geol. Soc. Spec. Publn. 182, pp 205-217.

Niswas, S. & Singhal, D.C., 1981. Estimation of aquifer transmissivity from Dar-Zarouk parameters in porous media. Journ. of Hydrology, 50, 393-399.

Pokar, M., West, J., Loke, M.H., 2001. Time lapse resistivity imaging on the Sherwood sandstone. Proc. 7th Meeting EEGS, Bermingham.

Reynolds, J.M., 1997. An introduction to applied and environmental geophysics. John Wiley & Sons.

Slater, L., Lesmes, D. & Sandberg, S. , 2000. IP interpretation in environmental investigations. Proc. SAGEEP 2000, EEGS.

Sorensen, K. 1995. Pulled array transient electromagnetic method (PA-TEM). Proc.. SAGEEP 1995. EEGS.

Sorensen, K. 1996. Pulled array continuous electrical profiling. First Break Vol. 14 No. 3, 85-90.

Sorensen, K. & Sondergaard, V. 1999. Large scale geophysical mapping and its application for groundwater protection in urban areas. Proc. SAGEEP 1999, 481-486.

Sternberg, B.K., & Levitskya,T.M. 1998. Correlation between Laboratory and in-situ measurements of soil. Journ. Env. & Eng. Geophysics, Vol. 3, Issue 2, 63-70.

Swartz, M, Misstear, B., Farrell, E., 2000. The Permeability characteristics of Irish Tills. Joint Geotechical Society of Irekand/IAH (Irish Group) meeting.

Worthington, P.F., 2000. Recognition and evaluation of low resistivity pay. Petroleum Geoscience, Vol. 6, pp 77-92.

5. Remedial Options for a Diesel-Contaminated, Confined Gravel Aquifer

Graham Webb, Manager Soil & Groundwater (Ireland), URS Dames & Moore

REMEDIAL OPTIONS FOR A DIESEL-CONTAMINATED CONFINED GRAVEL AQUIFER

GRAHAM WEBB – URS DAMES & MOORE

ABSTRACT

URS recently completed a series of soil and groundwater investigations within a site used for the storage and dispensing of diesel. The site is located close to the River Liffey in Dublin. The investigations found the site to be underlain by a thin layer of fill material overlying 4m - 5m of gravelly silt and gravelly clay soils, which in turn were found to overlie sandy fine-to-coarse gravels. Groundwater was encountered in the gravels, with a rest water table level above the clay/gravel interface. Free phase diesel was observed on the water table in some of the monitoring wells. Product thicknesses of up to 500mm were measured. The free-phase product plume was estimated to cover an area of approximately 500m^2. A constant rate pump test was carried out in one of the monitoring wells to assess the properties of the gravel aquifer and the feasibility of drawing the water table down below the clay/gravel interface. Product bail down tests were completed in two of the monitoring wells to assess the thickness of diesel on the groundwater, and to observe the rate at which the product layer recovered over time. Information from the initial phases of investigation, together with data from the pump test and the product bail down tests was used to evaluate remedial options to remove the free-phase product plume from the groundwater.

1.0 INTRODUCTION

URS recently completed a series of soil and groundwater investigations within a site in Dublin used for the storage and dispensing of diesel. The suspected sources of subsurface impact, namely the diesel offloading area and adjacent diesel dispensing area, lie within 200m of the River Liffey. The river was considered the primary environmental receptor potentially at risk from operations at the site.

Following completion of the investigation, a remedial plan was developed, the aim of which was to remove free-phase product from the groundwater in order to reduce the risk of impact on the river.

This paper presents the environmental setting of the site in terms of local geology and hydrogeology, the extent of soil and groundwater impact observed during the investigations, and the remedial options considered in the development of a remedial plan for the site.

2.0 ENVIRONMENTAL SETTING

2.1 SITE GEOLOGY

The area of interest was found to be underlain by a thin layer of made ground (typically less than 1 m thick) comprising gravel fill and reworked soil, overlying naturally occurring gravelly silt and gravelly clay soils 4 - 5m thick. The silts and clays were found to overlie a fine-to-coarse sandy gravel unit which was water-bearing. Investigations at the site did not confirm the thickness of the gravels; however, information from the Geological Survey of Ireland indicated a likely thickness of between 4m and 8m. Regionally the gravel unit is underlain by stiff boulder clay and Carboniferous 'Calp' Limestone.

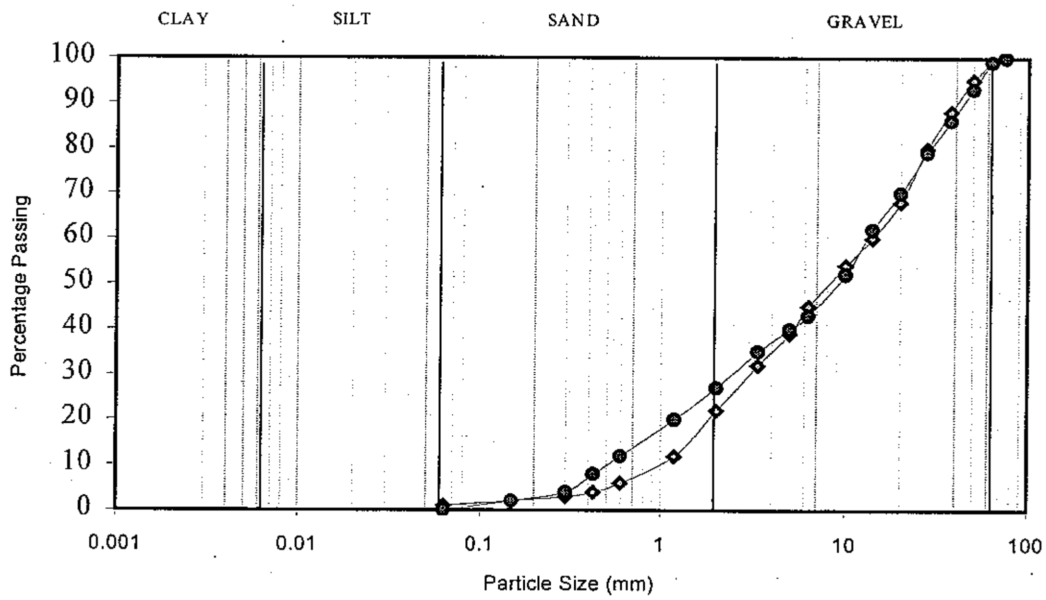
2.2 SITE HYDROGEOLOGY

During drilling of the investigation boreholes, shallow perched groundwater was observed in the fill material at some locations. Minor seepages of water were also observed in more permeable horizons within the silty clay.

Groundwater was encountered in the sandy gravel that was confined by the overlying silty clay. The static groundwater level was some 4 – 5m below ground level. The hydraulic gradient in the sandy gravel was shallow (ca. 1:1000) and generally towards the River Liffey. No tidal effect was observed in the monitoring wells; however, some seasonal fluctuation in the water table has been observed over time.

Based on the grain size distribution of the gravels (Figure 1), it was clear that they were highly permeable. A hydraulic conductivity of the order of 10^{-3} - 10^{-4} m/s (10 – 100 m/day) was estimated based on the grain size distribution.

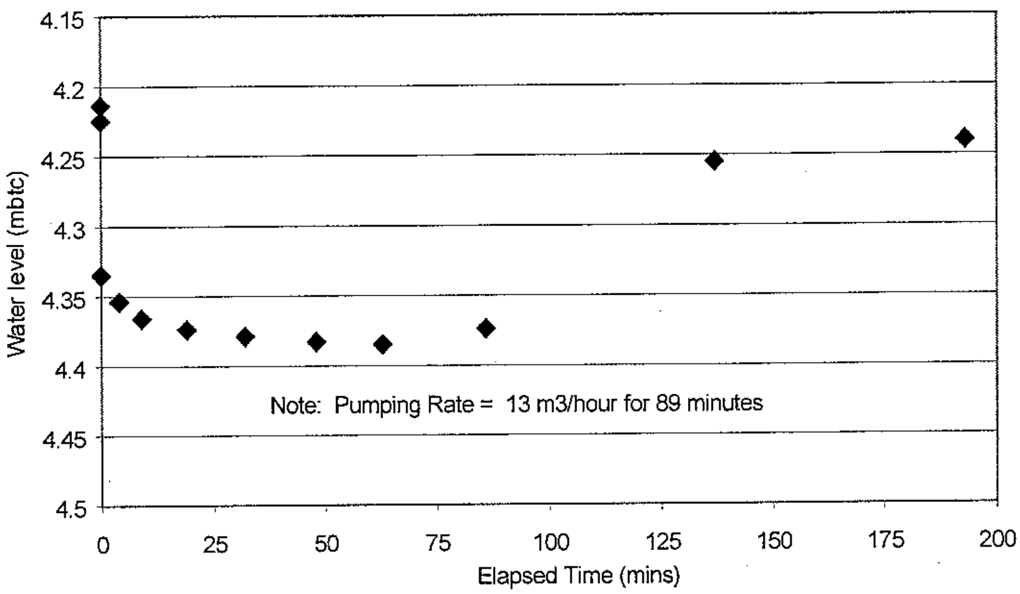
Figure 1 – Grain Size Distribution Curves for Gravel Samples



A constant rate pump test was subsequently performed within one of the monitoring wells. The data from the pumping test gave a hydraulic conductivity range for the gravels of between 3 x 10^{-3} and 4 x 10^{-4} m/s (40 – 260 m/day). Maximum draw-down in the pumping well was 160mm at a pumping rate of some 13 m^3/hour (Figure 2). Maximum draw-down of 20 – 30mm was observed in wells some 50m from the pumping well.

The pump test confirmed that any draw-down of the water table required as part of the remedial plan, would require pumping of significant volumes of water.

Figure 2 – Draw-down vs Time in Pumping Well



3.0 EXTENT OF SOIL AND GROUNDWATER IMPACT

3.1 EXTENT OF SOIL IMPACT

Nine soil sampling boreholes were drilled to a nominal depth of 3m using window sampling equipment. A number of the boreholes were drilled within the suspected source area, namely the diesel offloading area and the adjacent refuelling area, and the remainder were drilled 5 – 10m down-gradient of the suspected source area.

Mineral oil concentrations observed in the shallow soil (upper 2.5m) beneath the source area were consistently over 2,000mg/kg and the highest concentration was over 5,000mg/kg. Mineral oil concentrations in shallow soils 5 - 10m down-gradient of the source area were typically 1 - 2 orders of magnitude lower than in the source area.

Elevated mineral oil concentrations in soil (up to 5,000mg/kg) were also observed at the base of the gravelly clay in deeper boreholes drilled down gradient of the refuelling area. In such boreholes, evidence of free-phase product was typically observed in the underlying gravels during drilling.

3.2 EXTENT OF FREE-PHASE PRODUCT PLUME

Seventeen groundwater monitoring wells were installed across the site in three phases of investigation. The monitoring network was designed to delineate the lateral extent of any free-phase product plume and also to provide monitoring points down-hydraulic gradient of the product plume.

Information obtained from the initial two phases was sufficient to delineate the free-phase product plume generally to within 20 - 30m. The eight wells installed during the third phase were all located within the suspected plume area and were designed as product recovery wells. Free-phase product was found in nine of the 17 monitoring wells. The plume was found to extend some 20 – 30 metres down-gradient of the source area, covering an area of approximately 500m^2. A product thickness of over 500 mm was measured in two of the wells.

It was apparent that losses of diesel from fuel offloading and from refuelling had penetrated the ground in the source area and had migrated vertically down through the full extent of the clay unit to impact the underlying gravel aquifer. It had then migrated down-gradient, primarily within the gravel aquifer, and perhaps to a lesser degree within the saturated zone of the lower permeability clay soils.

The result is that product now lies on the water table, which typically rests within the silty clay soils overlying the gravels. It appears also that free-phase product has accumulated in the gravels in places and has been 'trapped' to a degree by the overlying clay soils. The confining clay soils appear to have limited the extent to which the free-phase plume has migrated down-gradient of the source area within the gravels.

3.3 EXTENT OF DISSOLVED-PHASE PLUME

The lateral extent of the dissolved-phase plume has not been studied in any detail to date. However, indications are that it is limited in extent. Mineral oil concentrations in a monitoring well some 70m down-gradient of the source area were found to be below the detection limit of 0.01 mg/l.

The available data suggests that the processes of natural attenuation are reducing dissolved-phase mineral oil concentrations down-gradient of the free-phase plume relatively rapidly, to the extent that the risk of the River Liffey being impacted is considered to be low.

4.0 REMEDIAL OPTIONS

4.1 INTRODUCTION

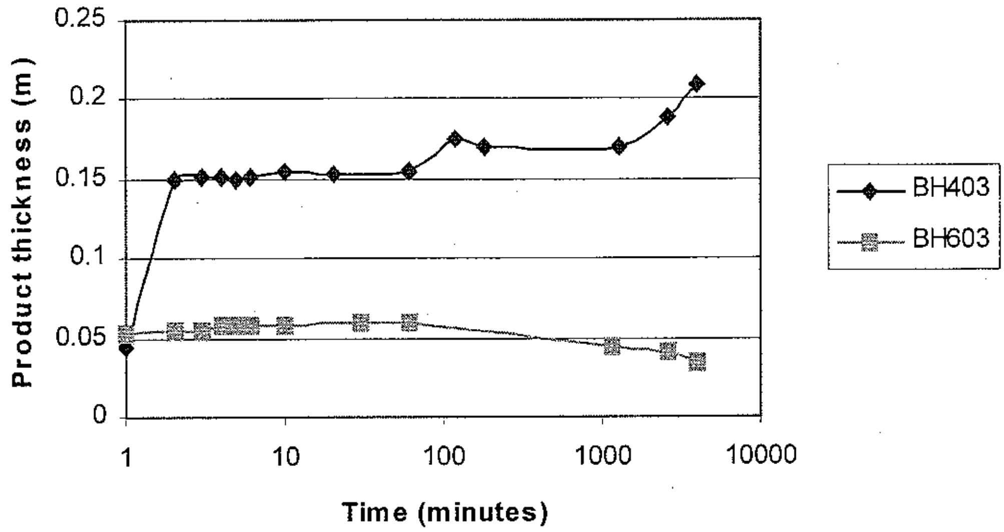
In developing a remedial plan for the site and selecting an appropriate remedial technology, it is important to consider where the bulk of the product actually lies. Is it mainly within the clay soils, or mainly within the gravels?

Secondly one needs to consider how to attract the product to the recovery points from the formation in which it rests. Different approaches may be required to recover product from the clay and from the gravel. In particular, the presence of the clay confining layer over the highly permeable gravels makes it difficult to 'move' product laterally through the gravels to recovery wells.

Thirdly, at the subject site there were operational constraints that needed to be taken into account in designing the remedial systems. In particular, the proposed locations of recovery wells and alignment of associated pipework were severely restricted by site operations, and redevelopment plans for the site further constrained the design of the remedial systems.

In order to answer the initial question (i.e. 'where is the bulk of the product?'), product bail-down tests were performed in the two monitoring wells where significant accumulation of product had been observed. The recovery of the product layer observed in the wells over time is plotted in Figure 3.

Figure 3 – Product Recovery vs Time



The product layer in BH403 recovered rapidly to 150 mm within minutes, then gradually increased over the following days. The initial product thickness in this well prior to the test was over 500mm. It is likely that the source of the initial influx of product into the well was from the permeable gravel unit. The subsequent gradual increase over time could have also been from the gravels; however, there may also have been a contribution from the clay soils.

The results of the product recovery test in BH603 suggest that there is little product in the gravels or in the clays in the vicinity of this well, and it may lie close to the edge of the product plume. The initial product thickness in this well prior to the test was approximately 100mm.

In the following section, a number of *in-situ* remedial techniques are considered in terms of their applicability to product recovery from gravels, and the particular situation observed at the subject site.

4.2 PASSIVE SKIMMING

Passive skimming involves skimming free-phase product that accumulates in wells, sumps or trenches installed within the product plume.

The main advantage of this technique is that it is relatively cheap in terms of both capital cost and operating cost. Further, a relatively low volume of contaminated water is produced. The disadvantage is that it can be a very slow process, insofar as there is no driving force (apart from the natural hydraulic gradient) to encourage product migration towards the collection points.

A common use of passive skimming would be the groundwater cut-off drain, installed across the groundwater flow path to control migration of a free-phase product plume. Product collecting in the drain can be readily skimmed off via a series of sumps installed along the length of the drain. However, installing such drains in gravels can be problematic if groundwater control or trench support is required during installation. In the subject case, operational constraints prevent the installation of sumps or trenches.

Passive skimming from a series of relatively closely spaced recovery wells is considered a viable option at the subject site. The plume appears not to be spreading and from the site's perspective there is no real time constraint to complete the remediation. In the subject case proprietary down-hole skimmer pumps would be used with inlets that float at the oil-water interface. The floating inlets are fitted with hydrophobic filters so that the volume of water recovered is reduced. The pumped liquids would normally be discharged directly to a holding tank, which is monitored on a regular basis and any water layer drawn off on an as-required basis. While passive skimming may not provide the total solution, it may be applied in association with another technique to meet the remedial goal.

4.3 GROUNDWATER ABSTRACTION WITH PRODUCT SKIMMING

By abstracting groundwater from a network of wells, a series of overlapping cones of depression is established in the water table, thereby increasing the piezometric gradient towards the collection points. Alternatively, a zone of groundwater depression can be established around a cut-off drain by abstracting from sumps installed within the drain. The aim is to encourage free-phase product to migrate into and accumulate in the zones of depression from where they can be recovered using skimmer pumps.

This technique is best applied to moderately permeable soils where zones of depression can be induced by pumping relatively modest volumes of water. The disadvantages of this technique include the following:

- it can generate a large volume of contaminated water that may require treatment prior to reinjection or disposal,
- product tends to be smeared across the soils within the zones of depression. This reduces the mass of product that can be recovered from the plume, and may limit the overall effectiveness of the clean-up programme,
- in permeable soils, or where only limited draw-down is achieved, there is a risk that the zones of influence around each well do not intersect, and as a result there may be zones where the remedial system is not successful. Similar difficulties may be encountered where the product is relatively viscous and may not readily migrate to the collection points.

In highly permeable gravels such as those found at the subject site, there is little benefit in pumping water, due to the limited draw-down attainable even at relatively high abstraction rates.

4.4 BIOSLURPING

The 'bioslurping' technique relies on the application of a vacuum to the wellhead in order to increase the piezometric gradient towards the recovery well, without inducing excessive draw-down of the water table. By reducing draw-down of the water table, product smearing is also reduced.

The technique involves connecting each wellhead to a vacuum pump via a pipe network. A riser pipe extends down the well casing to the oil-water interface (the aim being to recover more oil than water). A separator is located upstream of the vacuum pump to separate the oil and water from the air stream. The liquid phase is then passed through a conventional interceptor to separate the oil from the water.

The technique is an efficient means of recovering semi or non-volatile LNAPL (light non-aqueous phase liquid). Typically, recovery rates are significantly higher than those achieved by groundwater pumping and skimming. In addition, the applied vacuum induces air flow through the vadose zone that can enhance volatilisation and in-situ bioremediation of contaminants in the vadose zone soils.

The disadvantages of this technique are that capital costs, and perhaps more so operational costs, are typically higher than other more traditional methods. A sizeable power supply is required to run the vacuum plant. In addition the product tends to be recovered partly in free-phase form and partly as an oil-water emulsion. This emulsion then needs to be treated (normally off-site by an waste oil recycling company) to separate the oil from the water.

In technical terms, bioslurping would appear to be applicable to the subject site. However, the induced piezometric gradient may only be effective in enhancing migration of product from the clay soils, rather than from the gravels, where the bulk of the product appears to rest. Further, because of the high permeability of the gravels, the system is unlikely to be able to cope with fluctuations in the water table. Any fluctuation in the water table is likely to lead to the riser pipes either falling below the oil-water interface (and as a result only water would be recovered), or being left above the product surface, in which case neither oil nor water would be recovered.

Despite the limitations outlined above, from experience gained on other similar sites, initial recovery rates are likely to be good, but may be expected to decline following a few months of operation. It may therefore be appropriate to adopt this technique for an initial period, and to switch to an alternative technique once product recovery rates decline. In this way a timely and cost-effective solution may be offered to the client.

4.5 *IN-SITU* BIOREMEDIATION

In-situ bioremediation is traditionally not considered effective in the treatment of free-phase product plumes. However, URS has successfully used this technique in the past to remedy free-phase diesel in a permeable gravel aquifer, where the plume extended beneath a building. In that case, the remedial strategy involved batch addition of nutrients to a series of wells in the source area over a period of three years. Groundwater quality was monitored periodically via a series of wells down-gradient of the building, and product thicknesses (and groundwater quality in the latter stages) were monitored in the source area.

Such an approach in the subject case would undoubtedly take several years to complete; however, given the apparent stability of the plume and the lack of a time limit to complete the remediation, *in-situ* remediation (perhaps in conjunction with passive skimming) is considered a viable and relatively low-cost remedial option for the subject site.

5.0 CONCLUSION

A range of remedial options has been assessed in terms of their applicability to the subject site, where free-phase diesel lies both within the shallow gravel aquifer and in the overlying confining clay soils.

From a technical perspective, bioslurping would appear most likely to achieve positive results; however, it is also the most costly in terms of both capital cost and operating cost. Further, product recovery rates are likely to decline markedly following an initial period of operation (i.e. once product from the immediate vicinity of the recovery wells has been recovered) due to the site geology. Other remedial options that are considered technically viable, and likely to assist in providing an overall cost-effective solution, include passive skimming and *in-situ* bioremediation.

It is expected that a combination of these technologies will be applied at the site in order to meet the remedial goals.

6. The Role of Sand and Gravel Deposits in Vulnerability Assessment and Mapping

Donal Daly, Head of Groundwater Section, Geological Survey of Ireland.

THE ROLE OF SAND AND GRAVEL DEPOSITS IN VULNERABILITY ASSESSMENT AND MAPPING

Donal Daly
Groundwater Section
Geological Survey of Ireland

ABSTRACT

This paper describes the vulnerability concept as applied to groundwater protection in Ireland and concentrates in particular on the role of sand/gravel. Vulnerability assessments and maps are an integral part of groundwater protection schemes and are becoming an important means for land-use decision-makers to take account of the geological materials overlying groundwater. The paper shows how vulnerability fits within the hazard-pathway-target model for environmental management. It emphasises the need to define and understand the precise part of the geological environment that is included within the vulnerability concept, as this affects the hydrogeological factors that determine the vulnerability. The paper shows that the vulnerability concept can be used not only to produce vulnerability maps, but also as an effective tool in site assessments of both contaminant movement and the likelihood of contamination of groundwater.

THE GROUNDWATER VULNERABILITY CONCEPT: GENERAL GEOLOGICAL AND HYDROGEOLOGICAL ASPECTS

DEFINITION

Vulnerability is a term used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which <u>groundwater</u> may be contaminated by human activities.

VULNERABILITY AS A GENERAL CONCEPT

The vulnerability concept is based largely on the general question **'can water and contaminants move/get down to groundwater easily?'**

The vulnerability category assigned to a site or an area is based on the **relative ease** with which infiltrating water and potential contaminants may reach groundwater in a vertical or subvertical direction. As all groundwater is hydrologically connected to the land surface, it is the effectiveness of this connection that determines the relative vulnerability to contamination. Groundwater that readily and quickly receives water (and contaminants) from the land surface is considered to be more vulnerable than groundwater that receives water (and contaminants) more slowly and in lower quantities. Also, the slower the movement and the longer the pathway, the greater is the potential for attenuation of many contaminants.

Conceptually therefore, the vulnerability can be related to the recharge acceptance potential or the recharge rate at any given site or area:

- in areas where recharge occurs more readily, a higher quantity of introduced contaminants will have access to groundwater;
- in areas where recharge is rapid, contaminants may quickly enter groundwater.

GROUNDWATER VULNERABILITY - A COMPONENT OF RISK AND RISK MANAGEMENT

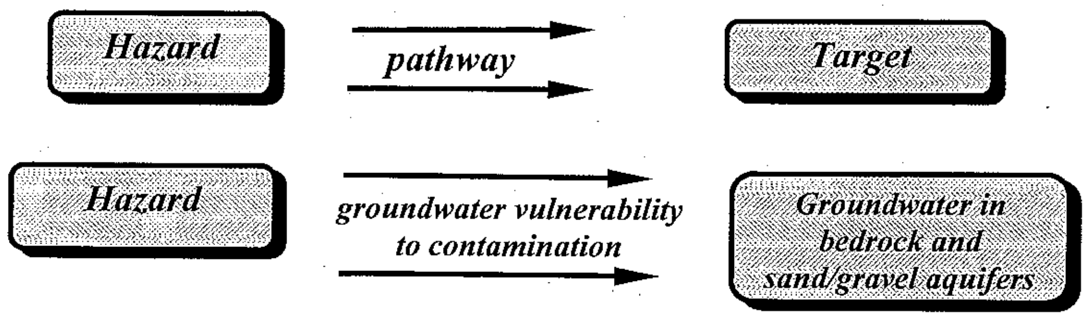
'Hazard-pathway-target'

The conventional hazard-pathway-target model for environmental management is useful when applying the risk concept to groundwater protection and vulnerability.

Hazard: These are the developments and activities that pose a threat to groundwater. Point sources of pollution pose the greatest threat to groundwater in Ireland, therefore **vulnerability mapping assumes that the point of release of contaminants is 1-2 m below ground level.** For vulnerability assessment in site specific situations, the (potential) point of release of contaminants is either known, in the case of existing developments, or can be obtained from development plans, in the case of new proposed developments. It may be at the ground surface for activities such as landspreading of piggery slurry or 5 m bgl for developments such as storage tanks or landfills. **The potential point of release of a contaminant is a critical reference point for vulnerability assessment and mapping.**

Target: The target (or receptor) is the water which has to be protected. This needs to be precisely defined. In the Irish groundwater protection scheme, **the target is groundwater in bedrock and in sand/gravel aquifers,** and is not, for instance, groundwater in tills, wells or 'major aquifers'.

Pathway: The pathway includes everything between the hazard and the target. It is **from the point of release of contaminants through geological materials and layers to the groundwater (target).** The pathway is characterised by the groundwater vulnerability.



The Link between 'Vulnerability' and the 'Pathway'

Vulnerability is based on evaluating the relevant hydrogeological characteristics of the geological materials along the pathway. Therefore it is assessed on the basis of the (largely) vertical transport of recharge water and contaminants from the point of release of contaminants to the first groundwater encountered, whether in a bedrock or sand/gravel aquifer. This (target) will be the water table, where the water table is in the bedrock or sand/gravel, or alternatively it will be the top of the bedrock or sand/gravel where the water table or potentiometric surface is in the overlying subsoil. It will **not** be the groundwater encountered in overlying subsoils, because this groundwater is not given a value and is not used directly for water supply. Therefore, conditions along the pathway may be saturated or unsaturated or a mixture of both.

Vulnerability and Contaminant Type

The characteristics of individual contaminants are not taken into account in vulnerability assessment and mapping. (However, they are an important factor in hazard assessment and in determining groundwater protection responses for hazards.) As a consequence, account is only taken of those properties and attributes, which are not specific but which are relevant for all types of contaminants, and in particular for conservative contaminants which behave like water itself.

ATTRIBUTES UNDERLYING THE VULNERABILITY CONCEPT

The vulnerability of groundwater depends on three principal attributes of the subsurface materials along the pathway:

Attributes	Related questions, if a pollution event occurs
1. The time of travel (travel time or transit time or residence time) of infiltrating water and contaminants along the pathway.	How long will it take for contaminants to reach the groundwater?
2. The relative quantity of contaminants that can reach the groundwater/target.	What proportion of the contaminant load will infiltrate to groundwater? Will any run off instead?
3. The contaminant attenuation capacity of the geological materials along the pathway.	How much, if any, attenuation will occur before groundwater is reached?

These attributes are difficult to determine directly but they are, however, dictated by the geological and hydrogeological characteristics of the pathway through which water/recharge/contaminants travel.

In conceptualising vulnerability, the **travel time** is the easiest and simplest attribute to keep in mind. Also, the hydrogeological factors that determine travel time are the most influential in determining 2 and 3 above.

CORE ELEMENTS OF VULNERABILITY ASSESSMENT AND MAPPING

There are 2 core elements:

1. The protection provided by the geological materials/layers along the pathway, overlying the **groundwater**. The topsoil layer is **not** taken into account in **vulnerability mapping** because the point of release of contaminants is assumed to be below the bottom of the topsoil. However, it is taken into account in groundwater protection responses for hazards where the point of release of contaminants is at the surface (e.g. landspreading of organic wastes (DELG/EPA/GSI, 1999b). It is assumed that there is little or no attenuation in bedrock owing to its fissured nature. Therefore the **unsaturated zone in bedrock** is **not** included in vulnerability mapping and assessment.

2. **Type of recharge** (point or diffuse). This is termed 'flow concentration' in the European COST Action 620 Approach (Daly, *et al*, 2001) and 'infiltration conditions' in the German PI method (Goldscheider et al., 2000). It expresses the degree to which the protection provided by the geological materials (or overlying layers) is bypassed. This element takes account of karst areas where there is point recharge at swallow holes, collapse features, etc, with rapid flow to groundwater, bypassing of the soils and subsoils and minimal attenuation before groundwater (the target) is reached.

Therefore the only layers relevant to vulnerability assessment and mapping are:

- in the case of bedrock aquifers, the subsoils overlying the bedrock;
- in the case of unconfined sand/gravel aquifers, the overlying unsaturated sand/gravel. Note that here may be occasions, although they are not typical, where the sand/gravel is overlain by till. In these instances the sand/gravel aquifer is treated like a bedrock aquifer.

In summary:

- consideration of the overlying geological materials is restricted to the **subsoil layer**;
- the component of the pathway considered in **vulnerability assessment of bedrock aquifers** is between 2 reference points – either the point of release of contaminants (in the case of site vulnerability assessments) or 1-2 m bgl (in the case of vulnerability mapping) **to** the top of bedrock;
- the component of the pathway considered in **vulnerability assessment of unconfined sand/gravel aquifers** is between 2 reference points – either the point of release of contaminants

(in the case of site vulnerability assessments) or 1-2 m bgl (in the case of vulnerability mapping) to the water table.

VULNERABILITY AND GROUNDWATER PROTECTION SCHEMES

The groundwater protection scheme methodology (DELG/EPA/GSI, 1999a) in essence compartmentalises the range of hydrogeological settings, that determine the likelihood of contamination in Ireland, into four categories – extreme (E), high (H), moderate (M) and low (L). Therefore, the entire land surface can be subdivided into these four main vulnerability categories.

Vulnerability classifications can be applied to two relevant scenarios:

- regional scale **vulnerability mapping**; and
- **site vulnerability assessment,** where relevant site investigation data are available.

The reason for considering these separately is that for a development on a site the point of release of contaminants is known and, depending on the development, can vary from ground level to several metres bgl.

The geological and hydrogeological basis for vulnerability mapping and site assessment of vulnerability are summarised in Tables 1 and 2.

Table 1 Geological and Hydrogeological Conditions Governing Vulnerability Mapping

Thickness of overlying subsoils	**Hydrogeological Requirements for Vulnerability Categories**				
	Diffuse recharge / **Subsoil permeability and type**			**Point Recharge**	**Unsaturated Zone**
	high permeability (*sand/gravel*)	moderate permeability (*sandy subsoil*)	low permeability (*clayey subsoil, clay, peat*)	(*swallow holes, losing streams*)	(*sand & gravel aquifers only*)
0–3 m	**Extreme**	**Extreme**	**Extreme**	**Extreme (30 m radius)**	**Extreme**
3–5 m	**High**	**High**	**High**	**N/A**	**High**
5–10 m	**High**	**High**	**Moderate**	**N/A**	**High**
>10 m	**High**	**Moderate**	**Low**	**N/A**	**High**

Notes: (i) N/A = not applicable.
(ii) Release point of contaminants is assumed to be 1–2 m below ground surface.
(iii) Permeability classifications relate to the engineering behaviour as described by BS5930.
(iv) Outcrop and shallow subsoil (i.e. generally <1.0 m) areas are shown as a sub-category of extreme vulnerability.

(amended from Deakin and Daly (1999) and DELG/EPA/GSIa (1999))

Table 2. Geological and Hydrogeological Conditions Governing Site Vulnerability Assessment

Vulnerability Rating	**Hydrogeological Requirements** ***Below the point of release of contaminants***			
	Subsoil Permeability (Type) and Thickness			**Unsaturated Zone**
	high permeability (*sand/gravel*)	moderate permeability (*sandy till*)	low permeability (*clayey till, clay, peat*)	(sand/gravel aquifers only)
Extreme	0–2 m	0–1.5 m	0–1 m	0–2 m
High	>2 m	1.5–8 m	1–3 m	>2 m
Moderate	N/A	>8 m	3–8	N/A
Low	N/A	N/A	>8 m	N/A

Note: (i) N/A = not applicable
(ii) Permeability classifications relate to the engineering behaviour as described by BS5930.

VULNERABILITY AND SANDS/GRAVELS

INTRODUCTION

Sorted sand/gravel deposits (fluvioglacial, wind-blown, fluvial) are considered to generally have aquifer potential and have a 'high' permeability (see Tables 1 and 2). In certain circumstances, the proportion of fines (silt and clay) may be sufficient to warrant a 'moderate' permeability rating. A recent TCD/GSI joint research project is providing estimates on both the % fines and the permeability value that will be the thresholds between 'high' and 'moderate' permeability. The research findings will be available in the near future. Based on our experience to-date, well-sorted sand/gravel deposits will seldom have a 'moderate' permeability. Unless there is evidence to the contrary, well-sorted sand/gravel deposits should be assumed to have a 'high' permeability.

As shown in Tables 1 and 2, sands/gravels are relevant in two hydrogeological settings:

1. when the target is the water table in a sand/gravel aquifer; and
2. when the target is the water table in a bedrock aquifer and the overlying subsoil is sand/gravel.

A third setting may occasionally arise where a sand/gravel aquifer is overlain by till or other non sand/gravel subsoil. In this situation the sand/gravel is considered in a similar way to a bedrock aquifer.

SAND/GRAVEL AQUIFERS

Relevant Hydrogeological Parameter

Sand/gravel deposits are classed as aquifers by the GSI when they have a certain minimum extent and saturated thickness. These values are normally 1 km^2 and 5 m, respectively.

Where the subsoil overlying the water table is sand/gravel, the only relevant parameter in vulnerability assessment and mapping is the thickness of the unsaturated zone.

An illustration of the hazard-pathway-target concept as applied to sand/gravel aquifers is shown in Figure 1.

Vulnerability Mapping

In vulnerability mapping, the cut-off point between extreme and high vulnerability is 3 m unsaturated topsoil and sand/gravel. (Note that in vulnerability mapping, the point of release of contaminants is assumed to be 1-2 m bgl.) In practice, with the exception of sand/gravel aquifers in lowlying areas, such as river flood plains, most sand/gravel aquifers will be classed as 'highly' vulnerable.

Site Assessments

In assessing the vulnerability on a site, for instance for an EIS or an IPC license, the point of release of contaminants will be known. It may be at the ground surface or several metres below ground level. The threshold point between 'extreme' and 'high' vulnerability is 2 m below the (potential) point of release of contaminants.

SAND/GRAVEL OVERLYING BEDROCK AQUIFERS

This situation arises where the sand/gravel is either too limited in extent or has an insufficient saturated thickness to be classed as an aquifer.

Relevant Hydrogeological Parameters.

Where bedrock aquifers are overlain by sand/gravel, the only relevant parameter in vulnerability assessment and mapping is the thickness of the 'highly' permeable sediments. The degree of saturation of the sand/gravel is **not** taken into account.

An illustration of the hazard-pathway-target/receptor concept as applied to sand/gravel above bedrock aquifers is shown in Figure 1.

Vulnerability Mapping
The thickness threshold between 'extreme' and 'high' vulnerability is 3m of topsoil and sand/gravel.

In view of the 'highly' permeable nature of sand/gravel, the groundwater in bedrock aquifers in these areas will never have a 'moderate' or 'low' vulnerability, irrespective of the thickness of the sand/gravel.

Site Assessments
The threshold between 'extreme' and 'high' vulnerability is 2 m sand/gravel beneath the (potential) point of release of contaminants.

SUMMARY

- Vulnerability represents the **relative ease** with which infiltrating water and potential contaminants may reach groundwater.
- Vulnerability should be conceptualised in terms of the **hazard-pathway-target** model.
- Hazards are the developments and activities that pose a threat to groundwater.
- The target is the first groundwater encountered in an aquifer.
  - In **bedrock**, the target is the water table, where the water table is below the top of the bedrock, or alternatively, the top of bedrock, where the aquifer is fully saturated.
  - In **sand/gravel aquifers**, the target is the water table, where the water table is below the top of the sand/gravel deposit, or alternatively, the top of the sand/gravel, where the water table or potentiometric surface is in the overlying (non sand/gravel) subsoil.
  - Groundwater encountered in tills or other non-aquifer subsoil is not considered to be a target.
- The pathway for water and contaminants is from the point of release of contaminants vertically to the target.
- Vulnerability is based on evaluating the relevant hydrogeological characteristics of:
  - the protecting geological layers along the pathway; and
  - potential bypassing of these layers.
- Bypassing of the protecting layers can occur where water flows rapidly underground, with minimal attenuation, at karst features such as swallow holes and dolines.
- For bedrock aquifers, the relevant geological layer is the subsoil, and the reference points for vulnerability assessment are (1) the point of release of contaminants and (2) the top of bedrock. The unsaturated bedrock layer is **not** taken into account as it is assumed that there is little or no attenuation in bedrock owing to its fissured nature.
- The relevant geological and hydrogeological characteristics of the protecting subsoil layer over bedrock are the **permeability** and **thickness**.
- In the case of sand/gravel aquifers (not overlain by other sediments), the relevant geological layer is the unsaturated zone; and the reference points for vulnerability assessment are (1) the point of release of contaminants and (2) the water table.
- The relevant hydrogeological characteristic of the protecting layer (assuming it is sand/gravel) over sand/gravel aquifers is the **thickness of the unsaturated zone**.
- The range of permeability of Irish subsoils is compartmentalised into 3 classes – high, moderate and low.
- Sorted sand/gravel is assumed to have a 'high' permeability unless particle size analyses or permeability data indicate otherwise.
- The hydrogeological settings that determine the likelihood of contamination (if a contamination event occurs) are subdivided into 4 vulnerability categories – extreme (E), high (H), moderate (M) and low (L) (see Tables 1 and 2).
- Vulnerability classifications can be applied to two relevant scenarios:

- regional **vulnerability mapping**, where the point of release of contaminants is assumed to be 1-2 m bgl; and
- **site vulnerability assessment**, where the point of release of contaminants is known and, depending on the development, can vary from ground level to several metres bgl.

♦ **Vulnerability mapping:**
- Where the target is the water table in a **sand/gravel aquifer**, the threshold between 'extreme' and 'high' vulnerability is 3 m of unsaturated topsoil and sand/gravel (see Table 1).
- Where the target is the water table in a **bedrock aquifer overlain by sand/gravel**, the subsoil thickness threshold between 'extreme' and 'high' vulnerability is 3m of sand/gravel (including the topsoil) (see Table 1). Due to the 'high' permeability of the sand/gravel, the groundwater in the bedrock will never have a 'moderate' or 'low' vulnerability classification in this situation.

♦ **Site vulnerability assessment:**
- Where the target is the water table in a **sand/gravel aquifer**, the threshold between 'extreme' and 'high' vulnerability is 2 m of unsaturated sand/gravel (see Table 2).
- Where the target is the water table in a **bedrock aquifer overlain by sand/gravel,** the subsoil thickness threshold between 'extreme' and 'high' vulnerability is 2m of sand/gravel (see Table 2).

ACKNOWLEDGEMENTS

This paper is based largely on an initial draft of GSI guidelines for assessment and mapping of groundwater vulnerability prepared by Jenny Deakin and Donal Daly. The development of the vulnerability concept in Ireland has been aided by colleagues, too numerous to list here, both inside and outside the Geological Survey. Ray Weafer, Cartographic Unit, GSI, produced Figure 1.

This paper is published with the permission of Dr. P. McArdle, Director, Geological Survey of Ireland.

REFERENCES

Daly, D., Dassargues, A., Drew, D., Dunne, S., Goldscheider, N., Neale, S., Popescu, I.-C. & Zwalen, F. 2001. Main concepts of the "European Approach" for (karst) groundwater vulnerability assessment and mapping. Submitted to Hydrogeology Journal.

Daly, D. & Warren, W. P. 1998. Mapping groundwater vulnerability: the Irish perspective. *In*: Robins, N. S. (ed.) *Groundwater pollution, aquifer recharge and vulnerability.* Geological Society, London, Special Publications, **130**, 179-190.

Deakin, J. and Daly, D., 2000. County Clare groundwater protection scheme. Joint GSI/Clare County Council report. 67pp.

Department of the Environment and Local Government, Environmental Protection Agency & Geological Survey of Ireland. 1999a. *Groundwater protection schemes.* Geological Survey of Ireland, Dublin.

Department of the Environment and Local Government, Environmental Protection Agency & Geological Survey of Ireland. 1999b. *Groundwater protection responses to the landspreading of organic wastes.* Geological Survey of Ireland, Dublin.

Goldscheider, N., Klute, M., Sturm, S. & Hotzl, H. 2000. The PI method – A GIS-based approach to mapping groundwater vulnerability with special consideration of karst aquifers, Z. angew. Geol., 46 (3) : 157-166.

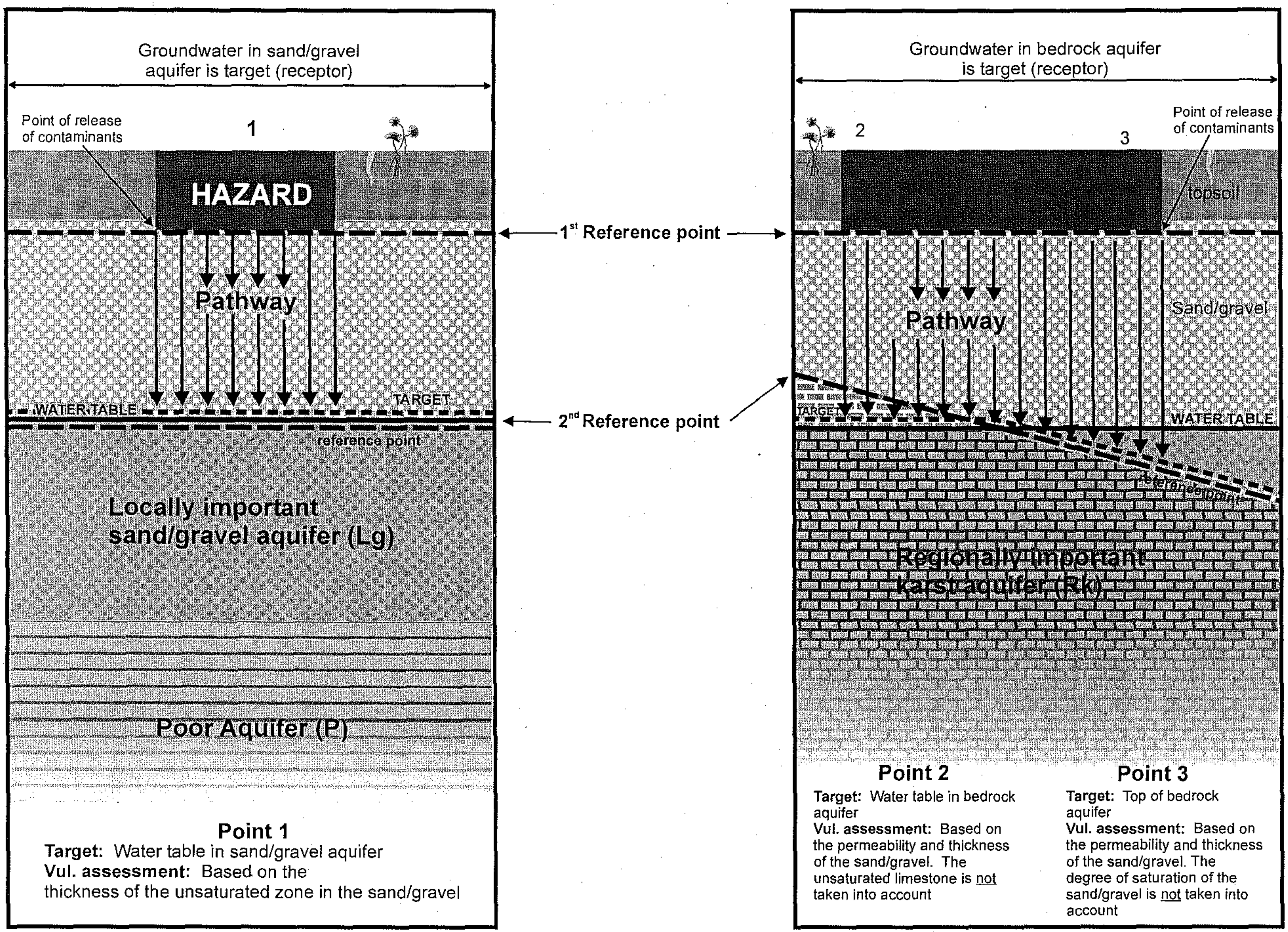


Figure 1. Illustration of the hazard-pathway-target concept and the hydrogological factors that govern vulnerability assessment. Vulnerability assessment is based in the relevant properties of the subsoil between the 1st and 2nd reference points.

7. Source Protection Issues – Scotland

Charles Jones, Principal Hydrogeologist, Mott MacDonald, Cambridge

SOURCE PROTECTION ISSUES - SCOTLAND

Charles Jones,

Principal Hydrogeologist, Mott MacDonald, Demeter House, Station Road, Cambridge CB1 2RS, UK

ABSTRACT

Source protection issues have been examined at two major wellfields in the NoSWA region of Scotland. Source protection zones have been derived for SEPA at three other sources. Comparisons are made with similar SPZ/GPZ work on over 200 sources in England and Wales. It is concluded that issues of data availability and reliability are common and that development of conceptual models is the critical task in all cases. Interaction with rivers, effective aquifer thickness and estimation of abstraction and recharge provide the main technical challenges. Transport models or tracer tests are very rarely available to verify assumptions made. A modified cylinder model is presented for use in high rainfall-recharge areas.

INTRODUCTION

Policy and legislative issues relating to groundwater protection in Scotland have been the subject of a comprehensive review as presented in Fox (2001). The Groundwater Protection Policy for Scotland, SEPA (1997) sets out the framework for source protection zones and more general protection of the groundwater resource. The policy document also contains a series of statements supported by matrices that show how policies would be applied in the different classes of source and resource protection zones. Lewis et al (2001) describe how groundwater vulnerability mapping, a key component of the Groundwater Protection Policy, is being undertaken using modifications to the system developed for England and Wales that will improve both accuracy and usefulness.

This paper reviews some of the issues addressed in studies leading to the calculation of source protection zones in the shallow gravel aquifers that are being exploited in the valleys of the Highlands.

BACKGROUND

In practice the approach adopted for calculation of an SPZ will be decided on the basis of whether there is sufficient data or need to justify use of some form of computer model or whether a simple manual 'model' will suffice. As in England and Wales, the Inner, Outer and Source Catchment zones (Zones I, II, and III) represent, respectively the larger of 50 m or 50 day travel times, the larger of 25% of the recharge area or the 400 day travel time and the recharge area itself. The review of the data available is made during the development of an appropriate conceptual model. The conceptualisation requires a series of questions to be answered, the confidence or plausible range of answers to each question then informs the decision whether to attempt a computer model or not.

The first problem is to decide is to decide what volume of abstraction to protect for the different time bases. This often has to determined in the absence of any guide values from a water order and at present there are no abstraction licenses either. Options could include historic use if such data are available or planned use if the owner has determined what level of abstraction is likely within the context of an overall water supply and demand strategy. Another approach would be to assume that the existing pump capacity is known or measurable and that the pump may operate continuously for 50 days but at a lower operating factor for the 400 days and steady state periods. Some form of Source Reliable Output calculation using the methods described in Beeson et al (1995), may exist and this could also be a guide but, again unlike England and Wales, there has been no regulatory imperative to do this kind of analysis and so they are rare.

The abstraction will be balanced by recharge and, possibly, a change in storage. The relative importance of river infiltration and rainfall recharge may be examined at a set of arbitrary proportions in the absence of anything more certain. Rainfall recharge is also uncertain where surface runoff and actual evapotranspiration are unknown. Baseflow separations can be misleading if there is upstream storage or inter basin transfer for hydropower or if there are significant areas of upland bog.

Studies have shown how effective aquifer thickness can be easily overestimated in heterogeneous sands and gravels because relatively thin high permeability beds can provide fast pathways. There are many sites with poor geological records, no flow logging or step tests and so either a judgment must be made or a range of possibilities examined.

Effective permeability values are relatively easy to determine since some form of yield drawdown test is commonly available or easy to carry out and different combinations of permeability and thickness can be examined to achieve any measured transmissivity.

It is usually the case that effective porosity will be based on published laboratory results rather than field tests.

Lateral watertable gradients along the valley floor are unlikely to be measurable due to the sparse number of wells. A simple approach is to assume the watertable follows the ground surface and derive the gradient from topographic data in the valley.

After all these uncertainties have been grappled with, it comes as a relief to be able to apply a simple cylinder model to calculate the 50 day time of travel zone. If the resulting radius is smaller than the distance to a recharge boundary, the model will be quite robust. In contrast the 400 day zone may be much more likely to encounter a river or other surface water boundary. Furthermore, the standard cylinder model may require modification possibly using the formula derived below to take account of recharge from rainfall.

The simple approach to conceptualisation can be tested against a case history such as that presented in Chen (1997) where computer simulations have been undertaken.

CYLINDER MODELS

The standard cylinder model used in England and Wales for the calculation or checking of 50 and 400 days SPZs is as follows:

$$r^2 = Q * t / (pi * B * n)$$

where r = radius of protection zone (m)
Q = abstraction rate (m^3/d)
t = time of pumping (days)
B = effective aquifer thickness
n = effective porosity

The model is based on the simple concept that the time of travel from the circumference of the cylinder to the centre is such that the volume pumped equals the effective pore volume of the cylinder. However, if the porosity or thickness is small and the recharge is high, the calculated 400 day zone may be an unrealistically large proportion of the total catchment zone. The simplest modification to the cylinder model can be made assuming that all the effective rainfall also reaches the centre of the cylinder in the same time. The volume of effective rainfall (V_r) is given by:

$$V_r = pi * r^2 * P * t/1000$$

where P = effective precipitation (mm/d)

and thus:

$$r^2 = Q * t / (pi * (B * n + P * 10^{-3} * t))$$

REFERENCES

Beeson S, van Wonderen JJ & Misstear BDR (1995) “A methodology for the determination of outputs of groundwater sources”, London: UK Water Industry Research.

Chen M, Soulsby C & Willetts B (1997) “Modelling river–aquifer interactions at the Spey Abstraction Scheme, north east Scotland – implications for aquifer protection” QJEG **30** 123-136.

Fox IA (2000) “Groundwater Protection in Scotland” in Groundwater in the Celtic Regions, eds Robins NS and Misstear BRD, Geological Society London, Special Publication **182**, 67-70

Jones CRC & Singelton AJ (2000). “Public water supplies from alluvial and glacial deposits in northern Scotland”, in Groundwater in the Celtic Regions, eds Robins NS and Misstear BRD, Geological Society London, Special Publication **182**, 133-139

Lewis MA, Lilly A & Bell JS (2000) “ Groundwater Vulnerability mapping in Scotland: modifications to classification used in England and Wales” in Groundwater in the Celtic Regions, eds Robins NS and Misstear BRD, Geological Society London, Special Publication **182**, 71-79

Robins NS & Ball DF (1987), “Groundwater in the superficial deposits of Scotland - a review”. Applied Research and Development Report Number ARD, Scottish Development Department.

Watt GD, Mellanby JF, van Wonderen JJ & Burley M (1987), “Groundwater investigations in the lower Spey valley, near Fochabers”, Journal of the Institution of Water & Environmental Management, **1**, 89-103.

8. Gravel Aquifers - Integration of Groundwater Development and Source Protection

Kieran O'Dwyer, K.T. Cullen & Co. Ltd.

GRAVEL AQUIFERS

INTEGRATION OF GROUNDWATER DEVELOPMENT AND SOURCE PROTECTION.

Kieran O'Dwyer – K. T. Cullen and Co. Ltd.

Abstract.
Source protection schemes provide a clear picture of the hydraulic regime within the vicinity of an abstraction source and are a useful aid to planning personnel in adjudicating planning applications. The quality of a groundwater supply is assessed on its natural quality whereas water supplies from surface water source are assessed on the quality of the treated water (the risk to the health of the consumer). Gravel aquifers are more conducive to source protection scheme than fracture flow systems as the input parameters are more easily determined. Protection schemes involve risk assessment and risk management. The risk management response matrices should consider the degree of treatment of the supply. Should highly vulnerable gravel aquifers be regarded as surface water sources with appropriate treatment? Source Protection Schemes impact on third parties who may seek compensation. The response matrix for landspreading does not cover routine slurry spreading. Disinfection of gravel sources should be mandatory (particularly for group schemes.)

INTRODUCTION.

In the present economic climate the rate of development (Public and Private) has outstripped the rate at which essential infrastructure can be provided to these new developments by the local authorities. To this end it has become necessary to provide the required water supply, wastewater treatment plants and disposal systems as an integral part of the development itself. In many instances groundwater has become the preferred source for these small-scale public water supplies as it is frequently available in areas where there is an absence of surface water resources. Groundwater has the advantage that it generally requires less treatment than surface water abstractions. Routine disinfection should be recommended for any public water supply. However many private Group Water Supply Schemes distribute the water without any treatment whatsoever. It is generally the quality surveys of these untreated group water schemes and private wells that results in the headlines on the deplorable state of our drinking water quality. I would suggest that this is not a fair picture of the current state of Irish groundwater quality. Nonetheless it is essential that the resources are protected and to this end the GSI, DOE and EPA have drafted guidelines for the protection of groundwater. This paper describes how a source protection scheme is produced and comments on some of the conflicts that exist between the development of a water supply and its protection. Gravel aquifers are a good example of how source protection schemes can complicate the development of supply wells as these aquifers are particularly vulnerable to contamination.

GROUNDWATER – A SUSTAINABLE RESOURCE.

Ireland has extensive groundwater resources that are presently not fully utilised. Mainland Europe is 70% dependant on groundwater whereas Ireland is estimated to be 25% dependant for drinking water. The source of the water is recharge from rainfall and if the abstraction is properly managed then our groundwater reserves are renewable and sustainable. The Geological Survey of Ireland have classified the aquifers of Ireland in terms of relative importance. The classifications vary from regionally important to locally important to poor. Gravel aquifers can vary in terms of importance but generally in coarse gravel deposits the individual well yields are high. Many gravel aquifers, though having high yielding wells are not classified as regionally important due the fact that they lack the extent to store regionally significant volumes of groundwater. Gravel aquifers are usually unconfined (lacking any significant clay cover). Consequently recharge is rapid and can occur extensively over the aquifer. Many of the unconfined gravel aquifers can be regarded as lakes that have been infilled with permeable sands and gravels.

GROUNDWATER -VULNERABILITY.

The concept of aquifer vulnerability classification has been introduced to provide some indication of how well protected certain parts of the aquifer are to contamination. The various classifications are shown in Table 1.

Vulnerability Rating	Hydrogeological Requirements				
	Subsoil Permeability (Type) and Thickness			Unsaturated Zone	Karst Features
	high permeability (sand/gravel)	moderate permeability (sandy till)	low permeability (clayey till, clay, peat)	(sand & gravel aquifers only)	Extreme (30 m radius)
Extreme	0-3.0m	0-3.0 m	0-3.0m	0-3.0m	-
High	>3.0	3.0-10.0m	3.0-5.0m	>3.0m	N/A
Moderate	N/A	>10m	5.0-10.0m	N/A	N/A
Low	N/A	N/A	>10.0m	N/A	N/A

Notes: (i) N/A = not applicable.
(ii) Release point of contaminants is assumed to be 1–2 m below ground surface.
(iii) Permeability classifications relate to the engineering behaviour as described by BS5930.
(iv) Outcrop and shallow subsoil (i.e. generally <1.0 m) areas are shown as a sub-category of extreme vulnerability.

(amended from Deakin and Daly (1999) and DELG/EPA/GSI (1999))

Table 1: GSI Vulnerability Mapping Guidelines.

In general the greater the thickness and the higher the clay content the vulnerability becomes less. It can be seen from the above table that all sand and gravel aquifers are classed as highly to extremely vulnerable. It should be noted that in areas where the aquifer vulnerability is low, it is more than likely that the risk of contamination of surface waters by nutrients will be high. due to the higher rate of runoff for similar rainfall events. These vulnerability classifications are based on the premise that the contaminant is released 1-2 metres below ground.

GROUNDWATER PROTECTION SCHEMES.

There have been a considerable number of developments in the field of groundwater protection over the recent past. These include;

a) Groundwater Protection Scheme Guidelines (DELG/EPA/GSI, 1999a)
b) The Wastewater Treatment Manuals published by the EPA.
c) The Implementation of the Nitrate Directive (91/676/EEC)

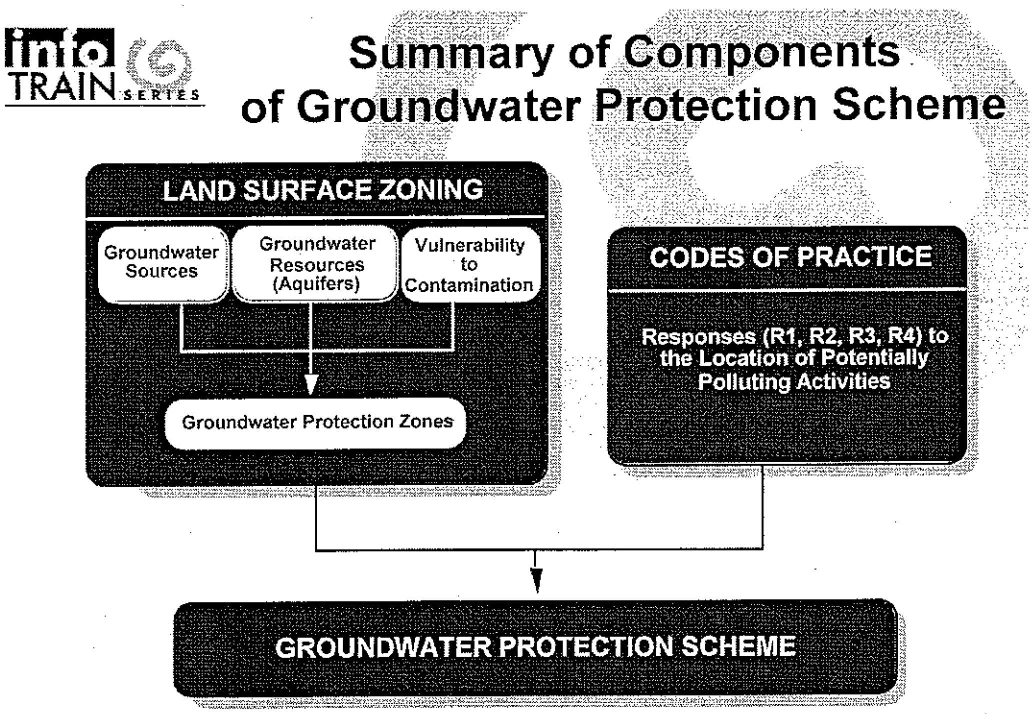
d) The Water Framework Directive (2000/60/EC)

Groundwater Protection Schemes are designed with the objective of assessing the vulnerability of the aquifer and providing a methodology for protecting:

The Aquifer (the resource)
and
The Source (point sources such as springs and water supply wells).

The methodology is developed in such a manner as to be easily implemented by local authority planning officials. If a robust groundwater protection plan has been drawn up, planning officials can adjudicate on planning applications for particular developments by referring to a series of maps and a response matrix. Most local authorities are developing or have developed groundwater protection plans. In some cases the focus has been limited to individual source protection rather than the aquifer as a whole.

The principal components of a groundwater protection scheme can are shown in the figure below.



A source protection scheme draws together data from operations carried out in the field and from various databanks such as that in the GSI together with other records (local drillers etc) to produce a clear understanding of the groundwater regime in the vicinity of the source. The inputs to the source protection plan can be summarised as follows.

- Groundwater Flow direction.
  Generally this is determined by drilling boreholes to produce a triangle of wells. The proposed **source** and two additional wells are used to produce this information. In some cases there may be some third party wells that can be used. Care should be taken when using nearby domestic wells as the pump cutting in and out can provide misleading data on the water table. The relative topographic water levels show the direction of groundwater flow in the immediate vicinity of the source. At further distances from the source the general topography is used to indicate the flow

direction.

- Hydraulic gradient.
  This is calculated using the three water levels in the wells.
- Transmissivity and Hydraulic Conductivity (permeability)
  The transmissivity data is derived from data collected during a pumping test on the source. The saturated thickness is known from the drilling log. The hydraulic conductivity is the transmissivity divided by the saturated thickness.
- The porosity of the saturated gravels. This is taken to be 25 – 40 %
- The abstraction rate.
  An additional 50% is added in order to provide for dry summer periods.
- The width of the ZOC is spread at an angle of 20° to allow for variations in flow directions.

The zone of contribution (ZOC) or catchment of the source can then be plotted on a map together with the zone of the 100 day travel time (Inner Protection Zone). The US EPA program WHPA is a useful tool for delineating the 100 day travel time zone. Other programmes such as MODFLOW or FLOWPATH. can also be used. However the results form these models have to be reviewed and a professional call has to be made and adjustments can be made to zones to reflect any uncertainties. The delineation of the zones for gravel aquifers is much easier than for fractured rock aquifers where many assumptions and guesstimates have to be made.

The **vulnerability** of the zone of contribution is mapped using data available from the various databanks, drilling records and field surveys. The wells drilled to provide the flow direction data are particularly useful in providing accurate data on the overburden composition within the inner protection zone.

The **aquifer classification** is then evaluated from the available information on the regional geology together with the data gathered from the drilling operations.

All of the above elements are combined to produce the **Groundwater Protection Zones** which constitutes the **risk assessment** element of the plan.

The Codes of Practice are used to evaluate the risk of a particular activity to the groundwater quality at the source and within the aquifer itself. These take the form of response matrices developed by the EPA, GSI and DoELG. This is the **risk management** element of the plan. To date there are response matrices for Landfills, Landspreading and Domestic Wastewater Treatment Plants. This allows the planning authorities to evaluate applications for developments within particular areas. The groundwater protection plans are also particularly useful in zoning areas in development plans.

CASE STUDY – GRAVEL SOURCE.

The case study described as part of this talk deals with a local authority groundwater well tapping into a shallow gravel aquifer on the outskirts of a midland town. It should be noted that other efforts were made to develop this supply from the bedrock aquifers in the area. The most suitable and highest yielding source was that in the gravels which was the most vulnerable. Cognisance had to be paid to the fact that there were a considerable number of potential pollution sources within the area. The establishment of the protection zones was helped by the fact that most of the inner protection area was in the ownership of the local authority. There was some evidence of minor bacteriological contamination in the production well (<10 faecal coliforms). However as this was a public supply it was proposed to disinfect as a matter of course. The faecal colifrom count in the raw water for most surface water abstractions is usually > 1000. The surface water directive (75/440/EC) catagorise surface water from which water for public water supply will be taken as A1, A2 and A3 depending on the increasing degree of treatment that will be applied. The faecal coliform limit for A1 waters which are the highest quality and require the least treatment is that the faecal coliform count must be less than 1000. There were major concerns on the part of the local authority as to whether they should develop this source. However there would have been very little such concerns if the source was a surface body with similar raw water quality. The groundwater protection zones provide a clear picture of the subsurface hydraulic regime in the area and allowed the water supply authority to instigate measures that would reduce contamination risk. In this case nearby houses, which had septic tanks were connected to the public sewer. The run off from the adjoining road was piped to a point outside the ZOC of the source. The source protection plan will use the response matrices when considering future development within the ZOC of the source.

GROUNDWATER DEVELOPMENT AND SOURCE PROTECTION.

We in the hydrogeological profession have spent many years lauding the superior quality of groundwater. A detailed methodology has been created for its protection. The most common groundwater supplies in the country are domestic wells. Virtually all of these receive no treatment. There is a belief that groundwater in its natural state should be pure and free from any contamination.

Source protection is aimed at protecting the health of the consumer. Groundwater with coliforms present is regarded as contaminated while surface water with coliforms present is classified as raw water. I believe that there is a strong argument that the response matrix for wastewater treatment systems should consider whether the supply is disinfected. This would be considered a further and essential element of the risk management element of the **source** protection scheme. Public water supplies from shallow gravels aquifers should be regarded in the same manner as surface water sources and a minimum level of treatment should be required (chlorination). Treated sewage is discharged to surface water bodies that are also sources of water supply. The risk to public heath is greatly reduced if a water supply is disinfected. In fact no public water supply (particularly group water supply schemes) should be distributed without disinfection.

There are difficulties for the planning authorities with respect to the protection zones, which often lie outside the planning application area. The protection zones can impose restrictions on the activities, which can be carried out on the adjoining lands. This can raise the question of compensation to neighbouring potential developers.

There is a perception that landspreading by farmers can be forcibly restricted within the Inner Protection Zone and there have been cases where compensation has been awarded to individual farmers for this inconvenience. Planning authorities have been known to request a written agreement with neighbouring landowners that no landspreading will be carried out. The landspreading response matrix has been formulated to deal with landspreading by IPC licenced activities. The Groundwater Protection Responses for Landspreading of Organic Wastes explanatory leaflet specifically states that for all other farming activities generating slurries landspreading should be carried out in accordance with the following guidance; (a)Control of Farm Pollution (DAFF 1992);and (b) Code of Good Agricultural Practice to Protect Waters from Pollution by Nitrates (DOE and DAFF 1996), incorporating current Teagasc Crop Fertility Recommendations and Production Techniques. If the well becomes polluted as a result of landspreading by a farmer in the vicinity of the well he can be prosecuted under the Water Pollution Act.

If a standard surface water abstraction is proposed for a water supply there are a lot less perceived inconveniences on neighbours (and consequently compensation and legal agreements) and less rules to obey in terms of protection. This does not make it right but it does make it less difficult.

SUMMARY AND CONCLUSIONS.

Groundwater Protection Schemes are a great step forward in environmental protection and reducing the risk to public health in the field of public water supply. It is important to compare like with like. Surface waters are regarded as the raw water for a drinking water supply while natural groundwaters are regarded as the supply itself. In a similar vein various reports may suggest that the quality of Irish groundwaters is poor. There has been a slight deterioration in the quality of Irish groundwaters in terms of nitrate concentrations. However there are very few areas where the nitrate concentrations exceed the drinking water MAC 50 mg/l. The 1999 survey by the EPA showed that 80% of the wells sampled (193) had concentrations less than the half the MAC.

Source Protection schemes are designed to assess and reduce the risk to public health. Therefore some consideration should be given to the fact that most public water supplies are disinfected and consequently the risk is less than if the supply was not treated.

Source protection schemes have proven to be a very useful tool for planners in adjudicating over permission for particular developments. However there are difficulties in dealing with restricting activities on lands outside the planning application area.

The response matrix for landspreading applies only to IPC licenced companies and activities.

There is a logical argument that gravel aquifers which are inherently extremely to highly vulnerable should be treated in the same manner as surface waters that are used for water supply. In reality shallow gravel aquifers are lakes that have been infilled with sands and gravels. Disinfection should be mandatory in any public supply.

9. The Curragh Aquifer - Current Conceptual Understanding and Numerical Modelling

Teri Hayes, Kevin Cullen, Stuart Sutton, and John Faherty. KT Cullen & Co. Ltd. and Entec (UK) Ltd.

THE CURRAGH AQUIFER

CURRENT CONCEPTUAL UNDERSTANDING & NUMERICAL MODELLING

By Teri Hayes, Stuart Sutton, Kevin Cullen and John Faherty
K.T. Cullen & Co. Ltd. & Entec (UK) Ltd.

Abstract

The Curragh Aquifer comprises sands, gravels and clays of glaciofluvial and glaciolacustrine deposits. These were deposited in a limestone trough at the end of the last glaciation. Glacial deposits up to sixty metres thick are encountered near the centre of the trough. This aquifer depth decreases to less than 20 metres at the edge of the Curragh plain. The vertical and lateral extent of the sediment type and inherent permeability varies depending on the glacial environment in which the sediments were deposited. In simplified terms a clayey till overlies sands and gravels. The primary discharge points for the aquifer are the springs and seepage zones in Pollardstown Fen in the north of the aquifer, springs (including the Japanese Gardens springs) and baseflow to the Tully River in the south and the Liffey Catchment in the east. As surface water drainage is absent from most of the aquifer recharge is high. Aquifer storage is relatively high and the regional groundwater regime shows little seasonal variation.

Based on the conceptual model of the aquifer, a credible groundwater mathematical model has been developed. This has permitted an acceptable assessment of the impact of a number of proposed road designs and construction sequences on groundwater levels and flows within the aquifer. Modelling has confirmed that the impacts associated with the final road design are within acceptable limits. Continuous updating of the model with field data ensures that the impact of construction activities can be measured to allow further mitigation if necessary. Confidence in the model and monitoring programme is essential for all stakeholders in the Kildare By-Pass project.

1 INTRODUCTION

The Curragh Aquifer (also known as the "Mid Kildare Gravel Aquifer") is an extensive gravel aquifer located in eastern Co. Kildare. A 4.5 kilometre section of the Kildare-Monasterevin By-Pass will be located in a cutting through the aquifer (Figure 1). Approximately 3.5 kilometres of this cutting will require dewatering to maintain dry conditions during construction and the installation of an impermeable liner for the final "tanked" section. Dewatering during construction will generate a cone of depression in the surrounding water table and subsequently alter the groundwater flow regime within the aquifer. As the aquifer discharges at springs in the Japanese gardens (a major tourist attraction) and Pollardstown Fen (a proposed Special Area of Conservation and supply to the Grand Canal), a clear and precise understanding of the impacts of dewatering on the groundwater regime was required by all stakeholders.

The initial section of this paper summarises the current understanding of the hydrogeology of the aquifer based on work undertaken prior to and, during this study. The latter section of the paper summarises the basis of the mathematical model and its implications for the road design to mitigate impacts on the sensitive receptors.

2 SITE SETTING

The Curragh Aquifer is located in an area of low relief, extending from Naas in the north to Nurney in the south, and from Kildare in the west to Killcullen in the east, (Figure 1). The Curragh is underlain by Carboniferous limestones and topographically rises to the "Chair of Kildare", an anticlinal ridge of porphyritic volcanic and sandstone bedrock of pre-Carboniferous age in the north–northwest. The aquifer as defined by G. Wright (GSI) extends to the Hill of Allen in the north, and to Dunmurry Hill and Read Hill in the west where bedrock comes close to the ground surface. To the southeast the aquifer is defined by outcrops of Lower Palaeozoic rocks (slates etc) of the Leinster Massif. Elsewhere the borders of the aquifer are less well defined. The overburden aquifer extent as implemented in the mathematical model is presented in Figure 1.

The Curragh Aquifer straddles the boundary between the Lifey & Barrow Catchments. Groundwater discharges to Pollardstown Fen in the north through a series of major springs and marginal seepages, ultimately discharging to the Grand Canal. To the south, groundwater discharges at a number of springs including those within the Japanese Gardens and provides baseflow to the Tully Stream, a tributary of the Barrow River and the Liffey River in the east of the aquifer.

3 GLACIAL ORIGIN

The Curragh Aquifer is dominated by glaciofluvial and glaciolacustrine deposits of Pleistocene Age. Charlesworth (1928) put forward the theory that Ireland was covered by an ice dome positioned in the north Midlands with its axis oriented northeast to southwest close to Donegal and Antrim. This theory suggests that the deposits in mid-Kildare are proglacial outwash gravels resulting from an ice margin retreating northward with meltwater draining southward to the River Barrow drainage system.

A more recent theory (Warren and Ashley 1994) suggests that Ireland was covered by an ice sheet with multiple ice domes centred in the north, central and south of Ireland during the last glaciation. Recent work undertaken by Glanville (1997) concur with the multiple dome theory suggesting that the sediments in the Curragh region were deposited from two retreating ice margins depositing sediments into an ice marginal lake.

Pollardstown Fen is located on the northeastern margin of the Curragh plain. Interpretation of sediments in the quarries excavated near the southern margin of the Fen suggest that the Fen was formed from meltwater flowing from the south through a narrow channel and depositing in a shallow flat bottomed lake basin (Glanville1997). Logs described by Glanville from this area are interpreted as glaciolacustrine fan sediments:fine sands (lower unit) overlain by gravels (middle unit) which are overlain by a gravelly diamicton (upper unit). The finer sediments (silts & clays) were encountered during drilling in the Fen plain during recent drilling by K.T. Cullen & Co. Ltd and earlier by the GSI (Daly 1981). The interpretation of the middle unit beds (foreset dip and fining to sediment eastward) suggest that they represent a prograding subaqueous fan or delta depositing into a body of standing water occupying the Fen with a sediment input point below the lake surface (Ashley and Smith 1995). The upper sediments are similar in lithology to the lower sediments and are believed to be a re-mobilisation or re-working of the upper units of the gravels during a local advance fluctuation in the ice margin.

The model suggested by Glanville and others is that a considerable amount of ponded water was required at the margins of the ice in order to accommodate the formations of a glaciolacustrine fan and deltaic deposits. One ice margin appears to have been located along the western margin of Pollardstown Fen and retreated in a westerly direction and another lay along the Ballysax fan moraine and retreated in a northerly/north-westerly direction. These margins were likely to be part of the same ice lobe. A third margin of a separate ice mass was located to the northeast of Kilcullen, which was retreated in a northerly or easterly direction. As these lobes retreated they uncoupled in the area of the present River Liffey basin, opening up an area where water ponded. The surface deposits of gravels in the Curragh may have been deposited as outwash into a shallow lake, which rapidly became sediment filled as the ice margins retreated and the shallow lake drained. Drainage was likely to be southwards along meltwater channels, southward from Kilcullen as seen today towards the Barrow and Slaney basins. As the ice margins retreated, lower ground to the north was opened and water could then flow towards the north in the present direction of the River Liffey. It is likely that the meltwater channel to the Fen occurred at this stage.

4 GEOLOGY & HYDROGEOLOGY OF THE CURRAGH GRAVELS.

4.1 Geology

To determine the nature and extent of the Curragh aquifer deposits, Cullen (1993) collated overburden stratigraphy information from archived mineral exploration and geological information provided by the Geological Survey of Ireland. As part of Kildare County Councils Project Specification (1997), 32 shallow boreholes into overburden and 5 deep boreholes to bedrock were installed in 1998 under the supervision of K.T. Cullen & Co. Ltd. These boreholes provided further information on the depth to bedrock and the glacial sequence (Kildare Town By-Pass, data sets used in the development of the conceptual and numerical models of the Curragh Aquifer 1999). From this dataset the base of the aquifer and the base of the overlying clayey till were defined.

The Curragh gravel occupies a trough in the limestone bedrock surface with the limits of the aquifer clearly defined in the west and northwest by more resistant sandstone and volcanic outcrop. Elsewhere the limits of the gravel aquifer are less clearly determined as the sand and gravel outwash deposits pass into clayey till dominated deposits. In general the glacial overburden cover is usually less than 20 metres thick in the area surrounding the Curragh. This increases to 20 – 40 metres at the edge of the bedrock trough. The maximum thickness encountered during the 1998 drilling programme was 60 metres.

As is typical of glacial sequences the Curragh aquifer shows little vertical or lateral continuity in sediment type. The thickness and extent of glacial till varies across the surface, as does the nature of the underlying glacial outwash deposits. This view is consistent with the changing and dynamic glacial environment in which these sequences were deposited. However, to represent a "worst-case" scenario, the mathematical model assumes both vertical and lateral continuity beneath the till deposits.

4.2 Hydrogeology

Watertable monitoring was undertaken in domestic wells in 1992/1993, (K.T. Cullen & Co. Ltd, June 1993). Since 1997, water level monitoring has continued at two weekly intervals in both domestic wells and the specially designed monitoring boreholes installed in 1998 (K.T. Cullen & Co. Ltd, 1998-2001). Local meteorological records and a total of 156 boreholes and standpipes are monitored two weekly to determine the recharge pattern. Monitoring points include 5 wells which are included in the EPA national database and which were previously monitored by the GSI, thus providing the longest monitoring record for the area. This data is analysed and recorded in quarterly monitoring reports to Kildare Co. Co. Figure 1b presents the current monitoring points and the interpreted groundwater flow regime.

As surface flow is absent in much of the area, recharge to the aquifer is considered to be high (350-450 mm/yr) and run-off is taken as minimal. Where the ground is steeper and depths of till increase some run-off to nearby rivers occurs. Groundwater discharges to the south of the road cutting at springs in the Japanese Gardens and further south in Kings Bog and Nurney Bog and to the Tully Stream. To the north groundwater discharges at Pollardstown Fen and the Miltown Stream. To the east the aquifer discharges to the Liffey catchment. The regional groundwater pattern (Figure 1b) varies little seasonally.

Meteorological data has been collated from nearby Osberstown. The aquifer hydraulics can be determined from an assessment of the many hydrographs produced as part of the monitoring programme. As indicated in the drilling logs the aquifer is not homogenous. Recent assessment has indicated that three recharge patterns occur within the aquifer. Limited reaction to recharge events is recorded in wells near the Fen and Japanese Gardens where discharge is occurring and the shallow gravel aquifer is constantly saturated and shows a slow reaction to rainfall events. Four wells in the south west of the aquifer are highly sensitive to recharge events. This pattern is indicative of low storage capacity in this area of the aquifer. Most wells within the mid-aquifer have a "typical" reaction to recharge events i.e. with lowest levels recorded in October rising to peaks in February/March. The annual fluctuations in the water table here is typically 1.25 – 2.5 metres, indicating a high storage aquifer (porosity c. 30 – 40 %). The response time to rainfall events in this area is generally two to three months depending on the thickness of clayey till within the overburden. Further work is currently been undertaken in the assessment of this data.

The Curragh aquifer is taken to operate as a single aquifer. This position is based on the known geological and groundwater flow pattern and is supported by hydrochemical data. Pumping tests as described in the K.T. Cullen & Co. Ltd 1993 report indicate a horizontal hydraulic conductivity value of 30 metres/day. However, a permeability value of 100 metres per day has been applied to the aquifer as a whole to reflect the observed water table fluctuations, the geology encountered in subsequent drilling and internal water balances.

4.3 Surface Flow data

Manual flow measurements have been undertaken at the various surface water discharges since 1997. The results show wide fluctuations in flow rates particularly in the Tully Stream, the

Milltown Stream and Milltown Feeder. Little information regarding discharges of groundwater to the River Liffey from this aquifer is available. Flows at major springs in the Fen were recorded manually where feasible, however flows at small springs and seepages are not available. Automatic flow recording equipment is currently being installed to allow further calibration of the model as required.

To overcome the difficulty of determining discharges as surface water flow from the aquifer, flow was taken to be proportional to the difference between the groundwater head and the elevation of the stream, spring etc, i.e. where the groundwater head is greater than the surface discharge point. These derived flows were compared with estimates from the sparse information available and observations of the various discharges.

In general the aquifer is considered to be semi-confined by the surface till deposits. The piezometric surface is located in a near surface layer. Therefore drainage for the road construction will result in a cone of depression extending out from the line of the cut, altering the natural groundwater flow regime. Removal of water from the cut area reduces the flow to the discharge zones. The impact of this reduction has been assessed by modelling, based upon the conceptual model outlined above and confirmed/modified by the on-going monitoring programme.

5 GEOLOGY & HYDROGEOLOGY OF THE FEN MARGIN

Drilling at the Fen prior to the 1997 study (Daly 1981) indicated a vertical thickness of 10 metres of [fen deposits underlain by gravel deposits. Recent drilling by K.T. Cullen & Co. Ltd indicated fen deposits of up to 17 metres at one location. Outflows at the Fen consist of free flowing springs and marginal seepages. Tufa is deposited at these discharge locations and particularly at seepage zones provides a habitat for rare species such as a microscopic snail (*Vertigo Geyeria*) protected by the Habitat Directive (92/43/EEC).

Artesian flow within the fen standpipes indicates that upward flow does occur. Presently the mathematical model allows discharge to the Fen solely based on the concept of upward flow and groundwater outflow from the upper part of the aquifer gravels. However, recent drilling work at the Fen margin indicates that the source of water at the seepages (habitat *Vertigo Geyeria*) may be due to recent recharge at the fen margin percolating through the very shallow till deposits. Further hydrochemical and recharge analysis is currently being undertaken to confirm this theory.

6 THE GROUNDWATER MODEL

6.1 Model Representation

The Kildare Aquifer Model, uses the public domain MODFLOW model code. Data input and output is managed through the Groundwater Vistas pre and post processing software package. Following the integration of the available information into a conceptual understanding of the gravel aquifer the model was constructed in 1998 and has evolved since that time to meet the changes in cutting design and construction programme.

The model is a four-layer representation of the Kildare Gravel Aquifer placed on a rectangular grid aligned with the National Grid. The basic grid size is 250m and this is progressively reduced in the region of the cutting to 62.5 m to permit realistic representation of the construction and dewatering sequence (Figure 2.1 and 2.2).

Model boundaries are set to coincide with the geological interpretation of the limits of the gravel aquifer and are effectively 'no-flow' boundaries with the exception of areas in the north-west and south-east where flows onto the aquifer can provide a source of runoff recharge and to the south-west of the Tully catchment where head dependant outflows could occur.

The aquifer is represented as a four layer (three gravel and one till) unconfined system. The base of the till and gravel are derived from information from about 150 boreholes and the upper till layer is not continuous across the area. The layered representation is necessary to represent the conditions that give rise to vertical flow, which is clearly an important mechanism in the support of Pollardstown Fen and minimal constraint is imposed on flow between layers.

The model is based on the conceptual understanding of the hydrogeological system derived from the synthesis of available hydrogeological, climatic and river flow data. In areas of uncertainty the assumptions adopted are invariably conservative (i.e. designed to ensure that that the predicted impact at the Fen is maximised). For example no flow is permitted from the underlying limestone into the gravel.

Recharge is calculated using actual rainfall and potential evaporation data (in the current realisation up to April 2001) and future predictions are based on a repetition of the May 2000 to April 2001 climatic sequence on a 'same day' basis.

6.2 Representation of Springs/Streams

Detailed representation of the fen is not attempted. The model predicts the impact of dewatering of water levels on the gravel aquifer and assumes no constraint between the aquifer and surface water features (streams, springs etc) on the basis that this again is a conservative assumption.

Rivers and springs are represented by cells which permit flow into or out of the aquifer proportional to the difference between stage or spring elevation and the water level in the aquifer.

Around the Fen individual springs and seepages are represented at or close to their observed levels and locations and a leakance factor (flow per unit head difference) that permits realistic representation of observed flow rates.

6.3 Representation of the Cutting

Dewatering of the cutting will proceed in stages from west to east progressively lowering groundwater levels to around 0.5 m below the base of the excavation in the section under construction. On completion and lining of each section groundwater levels will be controlled by drainage pipes set 1.75 m above the finished carriageway level.

The effect of dewatering is achieved using nodes which abstract water at a rate dependant on the difference between the natural groundwater level and these pre-set drainage levels but which do not permit water to enter the model when the groundwater level is below the drainage level. The conductance of these nodes is set at a high level that does not constrain the ability of the aquifer to deliver water to the drainage system.

Early model runs were based on construction in 500m steps in two-month periods with a break in construction from November through to the end of February. The most recent model run uses the Contractors proposed construction sequence with variations to allow for contingencies such as delays during the periods of highest volume dewatering.

6.4 Model Operation

The recharge input to the model occurs in daily time steps and the groundwater model operates in 15-day time steps. Model simulation with real climate data starts in January 1992 and current predictive output continues to the end of 2006, four years after scheduled completion.

For any one node model output can be obtained as a time series representation of either groundwater levels, or flows out of the groundwater system. The location of the data output points used (Figure 2.3) is controlled by the observation network, as confidence in the model predictions can only be developed from comparison with historical observation. Figure 2.4 provides examples of these comparisons. During model development iterations necessary to obtain these credible representations of reality were based on variations of hydraulic parameters within credible limits. The hydraulic parameters adopted as providing this credibility were:

	Hydraulic Conductivity (m/d)		Specific Yield	Specific Storage (/m)
	Hor	Ver		
• Gravel	100	4	0.13	0.0001
• Till	3	0.1	0.13	0.0001

2.5 Model Results

Throughout the period 1998-2001 the groundwater model has been used to represent a range of cutting designs and construction dewatering scenarios. The current predictive output run (KILD62) uses the Contractor' proposed dewatering sequence and real climate data to May 2001 with the final years climate data repeated through construction and up to the end of 2006.

A key output, both in that it is ultimately the source of any environmental impact and that it provides a means of anticipating such impact as dewatering is in progress is the outflow from the cutting (Figure 2.5). After construction measured outflows from the drainage system can also be compared with model predictions.

Figure 2.6 illustrates the predicted impact of the cutting outflows at four locations:

- The base flows from groundwater to Milltown Stream
- The groundwater levels close to the cutting (Obs Well 41)
- The groundwater levels midway between the cutting and Pollardstown Fen (GW3)
- The groundwater levels close to the Fen (GW4)

7 CONCLUSIONS

Establishment of a credible groundwater model of the Kildare Gravel aquifer has permitted a realistic assessment of the impact of a number of proposed road designs and construction sequences on groundwater levels within the aquifer. Sufficient data does not exist to permit detailed representation of the mechanisms that support the wetland cSAC at Pollardstown Fen. Consequently the groundwater impact predicted by the regional model represents the maximum credible limit of such impact. This groundwater prediction has in turn been used by ecological experts to assess the potential impact on the Fen ecosystem and has ensured that a final road design and monitoring mechanism has been adopted that constrains anticipated environmental impacts within acceptable limits.

Maintenance of the groundwater model as a live tool regularly updated with climate data and modified in response to flow and groundwater level observations during construction ensures that effective monitoring and control of construction activities is practicable. This is essential both for the management of construction activities and to provide confidence for all stakeholders in the preservation of the unique ecosystem that is Pollardstown Fen.

Acknowledgements

The work and results reported in this paper are product of many individual efforts but particular acknowledgement must be made of the contribution of Professor K. Rushton, who not only aided in the formulation of the conceptual understanding and design of the groundwater model but has acted as independent reviewer of the model output through much of the last three years.

Acknowledgement is also given to the immense contribution of the Working Group set up under Professor K Rushtons chair. This group involved Duchas and its consultants, Inland Waterways, the National Road Authority, Kildare Co. Co. and its consultants. The contribution of the Hydrogeology Subgroup (chaired by Dr Bruce Misstear) and Ecology Subgroup (chaired by Dr. G van Wirdrum) in the assessment of on-going monitoring and modelling data is gratefully acknowledged. Special acknowledgement is given to the staff of K.T. Cullen & Co. Ltd. who have worked over many years in the collection and interpretation of this data. These include K Fitzsimmons, V. Conlon, L. Brown, J. Rutherford, D. Ledwidge, S. Bradley and G Connell.

The support and understanding of Kildare County Council throughout the work period has been invaluable and their permission to present this data is gratefully acknowledged.

References

Charlesworth, J.K.(1928) *Glacial retreat from central and southern Ireland.* Quaterly Journal of the Geological Society of London.

Daly,D. 1981. *Pollardstown Fen. Hydrogeological assessment of Pollardstown Fen,*. GSI report.

Glanville,C. 19XX. *The quaternary geology of Co. Kildare, map descriptions for relevant 1:25,000 sheets,* GSI report.

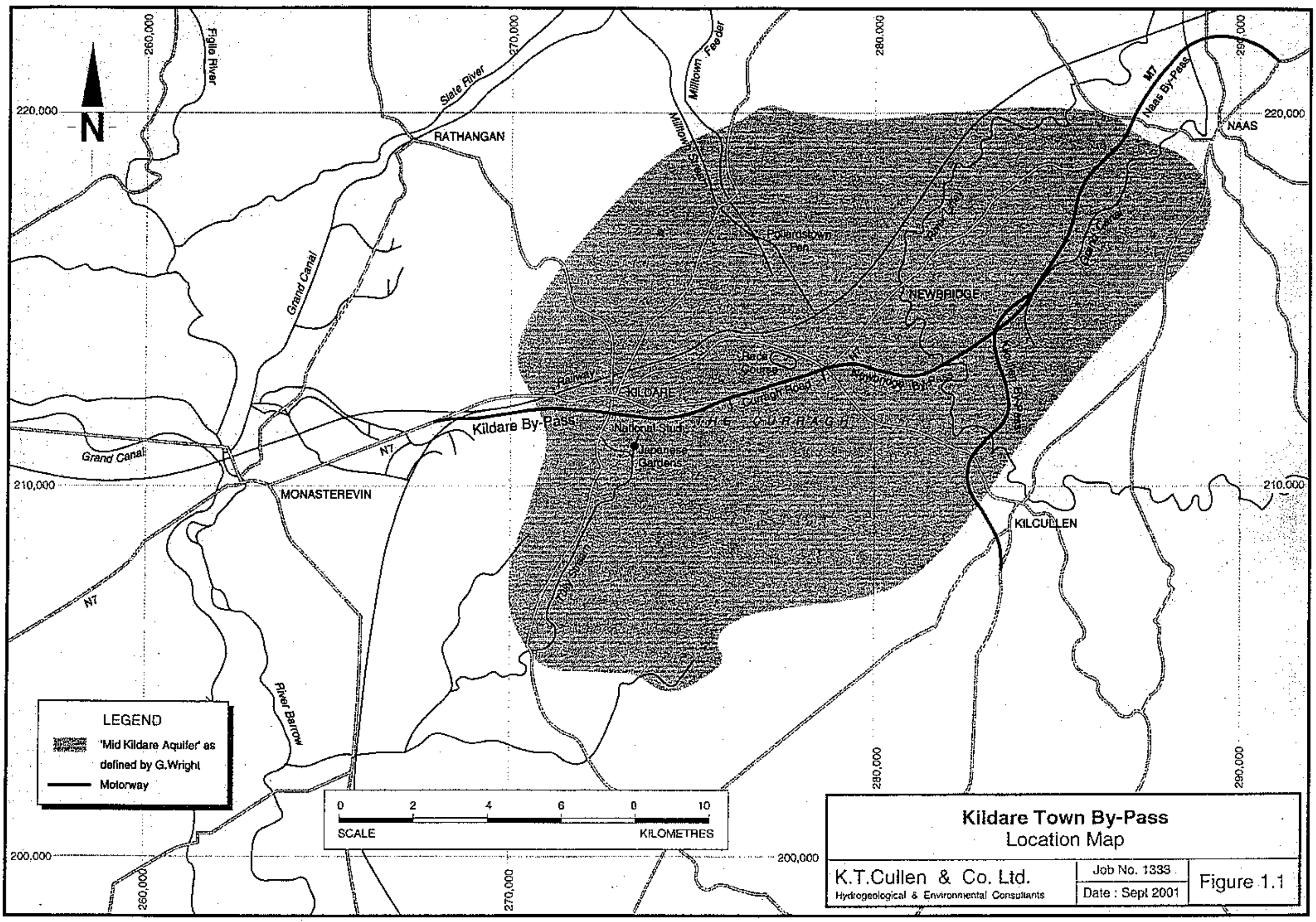
K.T. Cullen & Co. Ltd. 1993 *Kildare Town By-Pass*, Kildare Co. Co. Internal report

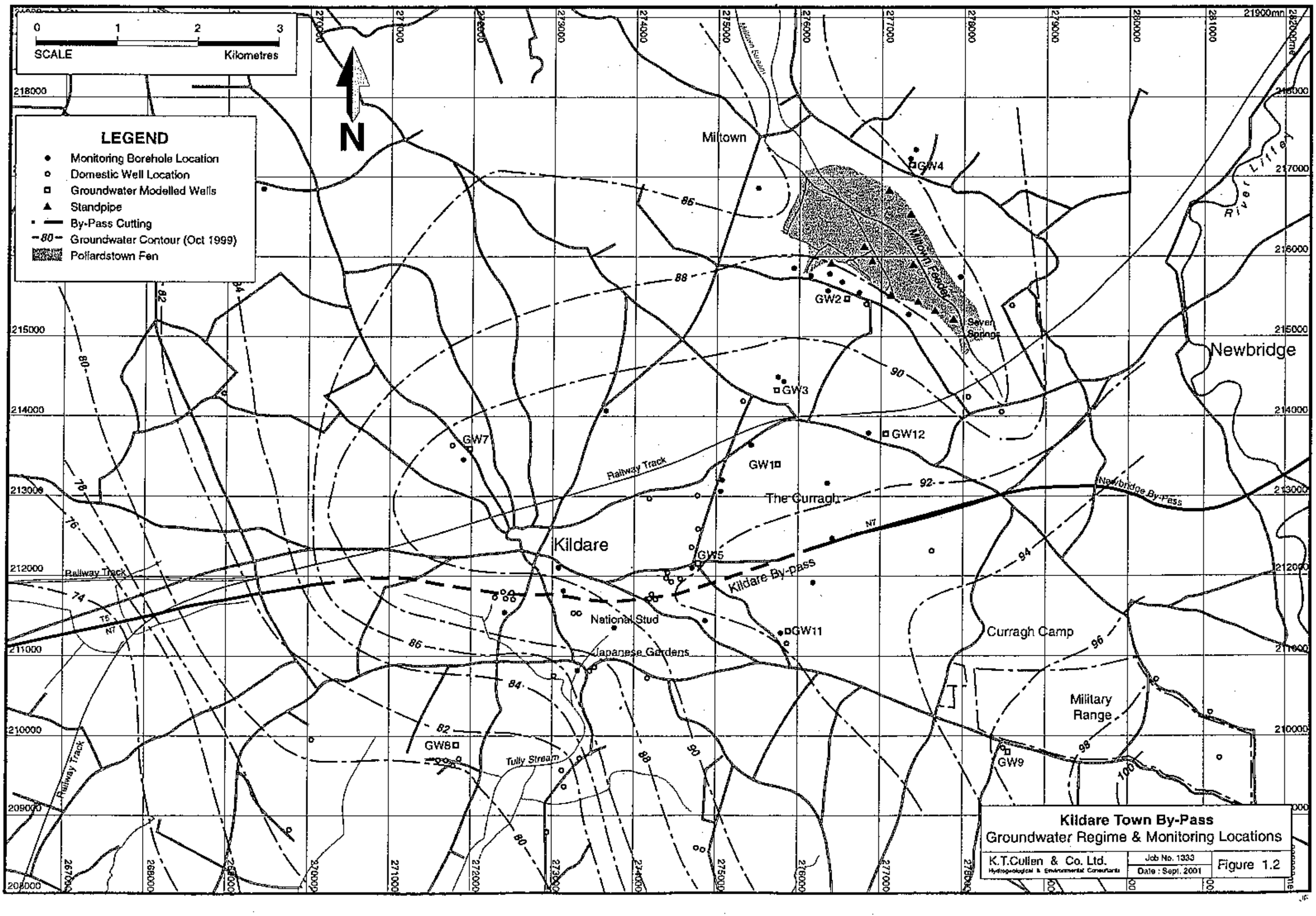
K.T. Cullen & Co. Ltd. 1999 *Kildare Town By-Pass, data sets used in the development of the conceptual and numerical models of the Curragh Aquifer*, Kildare Co. Co. Internal report.

K.T. Cullen & Co. Ltd. 1998-2001 *Kildare Town By-Pass, Quaterly Monitoring Report,* Kildare Co. Co. Internal reports.

Rushton, K.R. 1999 *Kildare Aquifer study completion report*, Kildare Co. Co. Internal report

Wright, G.R., 19XX, *The Mid-Kildare gravel aquifer,* Geological Survey of Ireland publication. Dublin.


Kildare Town By-Pass
Location Map
K.T.Cullen & Co. Ltd.
Hydrogeological & Environmental Consultants
Job No. 1333
Date : Sept 2001
Figure 1.1
LEGEND
'Mid Kildare Aquifer' as defined by G.Wright
Motorway
SCALE
KILOMETRES
0
2
4
6
8
10
N
RATHANGAN
NAAS
NEWBRIDGE
KILDARE
MONASTEREVIN
KILCULLEN
Pollardstown Fen
Race Course
Curragh Road
THE CURRAGH
National Stud
Japanese Gardens
Kildare By-Pass
Newbridge By-Pass
Naas By-Pass
M7
N7
Grand Canal
River Barrow
Slate River
Milltown Feeder
Figile River
Tully Stream
Railway
260,000
270,000
280,000
290,000
220,000
210,000
200,000


Kildare Town By-Pass
Groundwater Regime & Monitoring Locations
K.T.Cullen & Co. Ltd.
Hydrogeological & Environmental Consultants
Job No. 1333
Date : Sept. 2001
Figure 1.2
LEGEND
Monitoring Borehole Location
Domestic Well Location
Groundwater Modelled Wells
Standpipe
By-Pass Cutting
Groundwater Contour (Oct 1999)
Pollardstown Fen
SCALE
Kilometres
0
1
2
3
N
Milltown
Newbridge
Kildare
The Curragh
Curragh Camp
Military Range
National Stud
Japanese Gardens
Seven Springs
Milltown Feeder
River Liffey
Tully Stream
Railway Track
Kildare By-pass
Newbridge By-Pass
N7
GW1
GW2
GW3
GW4
GW5
GW7
GW8
GW9
GW11
GW12
74
76
78
80
82
84
86
88
90
92
94
96
98
100

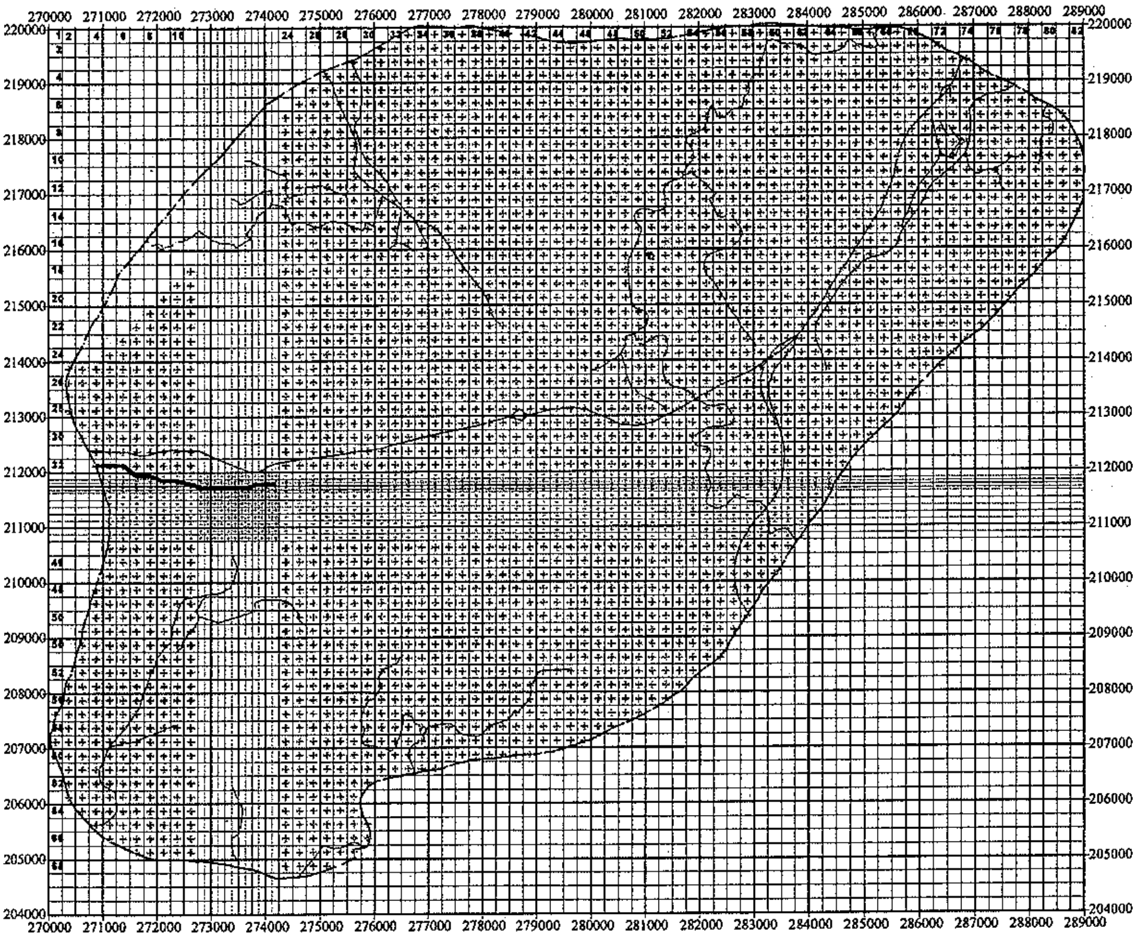


Figure 2.1 Model Extent and Node Positions

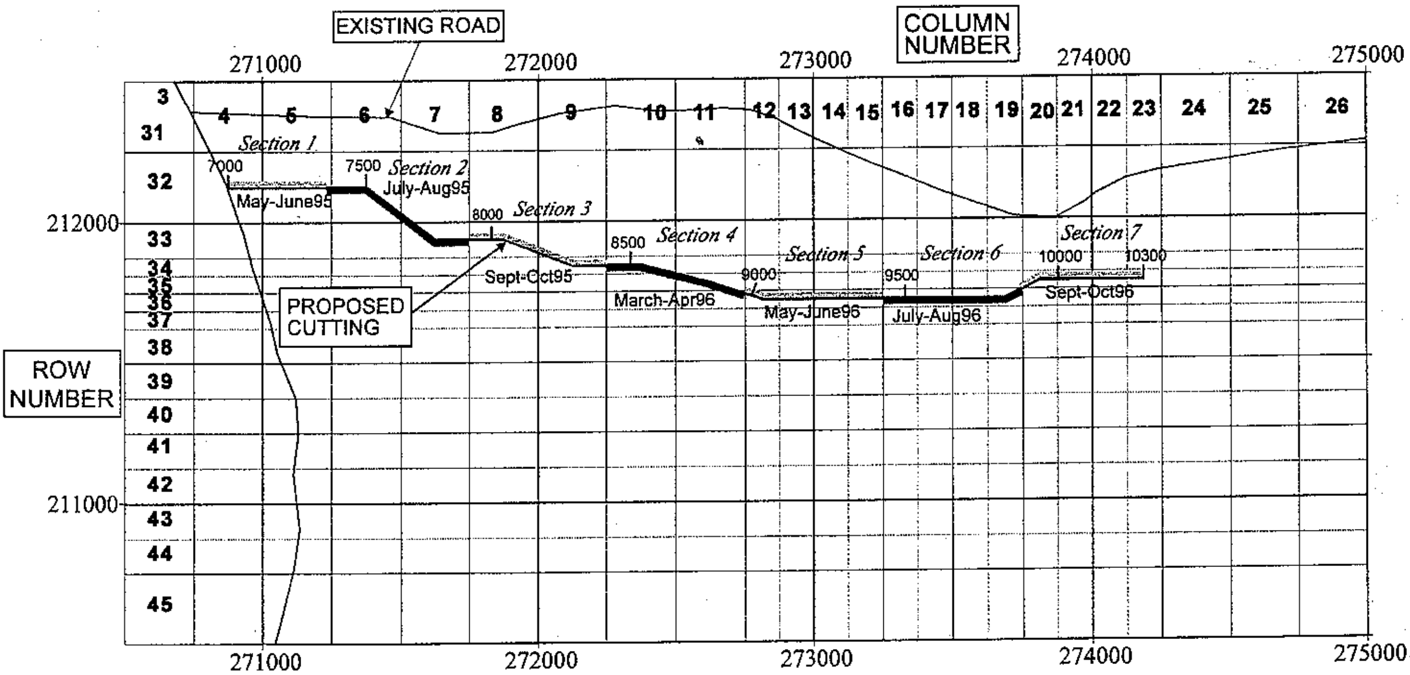


Figure 2.2 Detail of Model Grid Along Line of Cutting

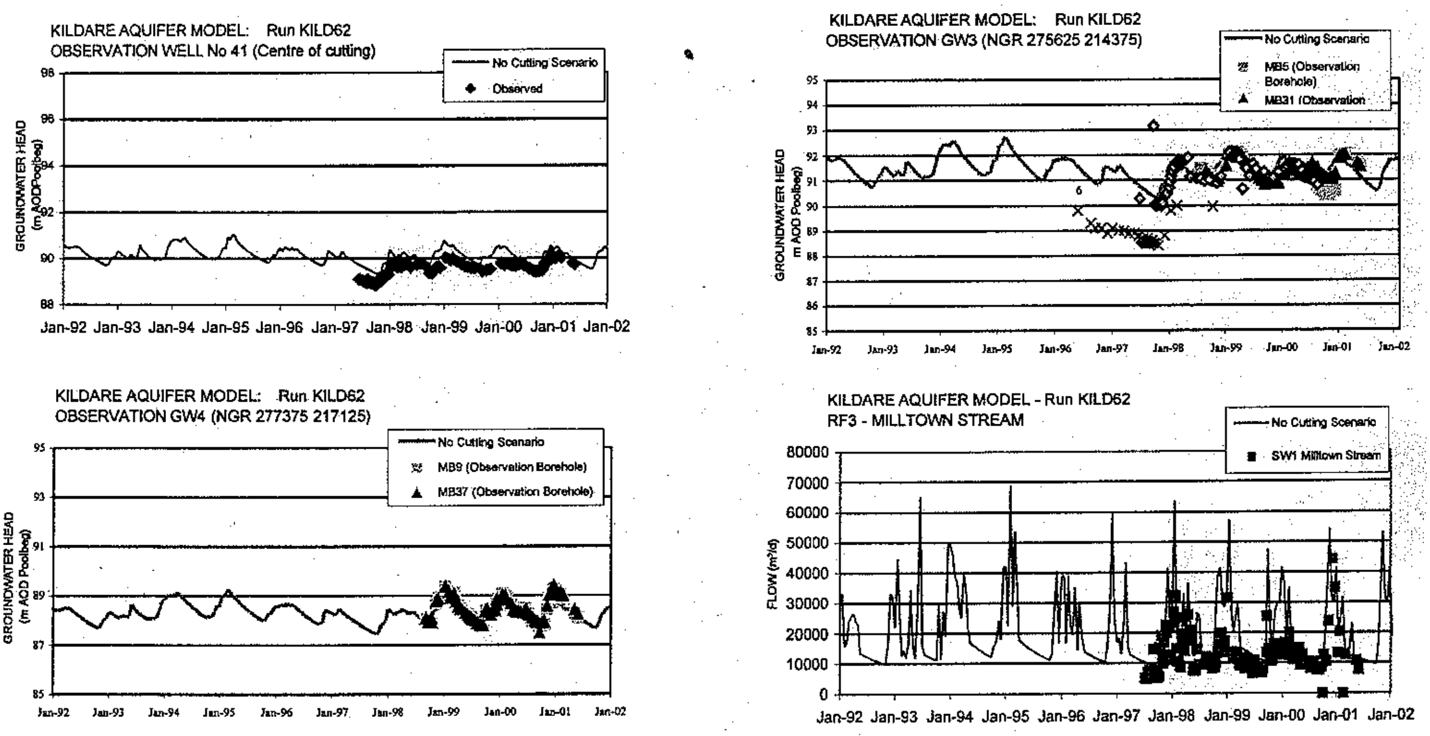


Figure 2.3 Comparison of Model Output and Observation

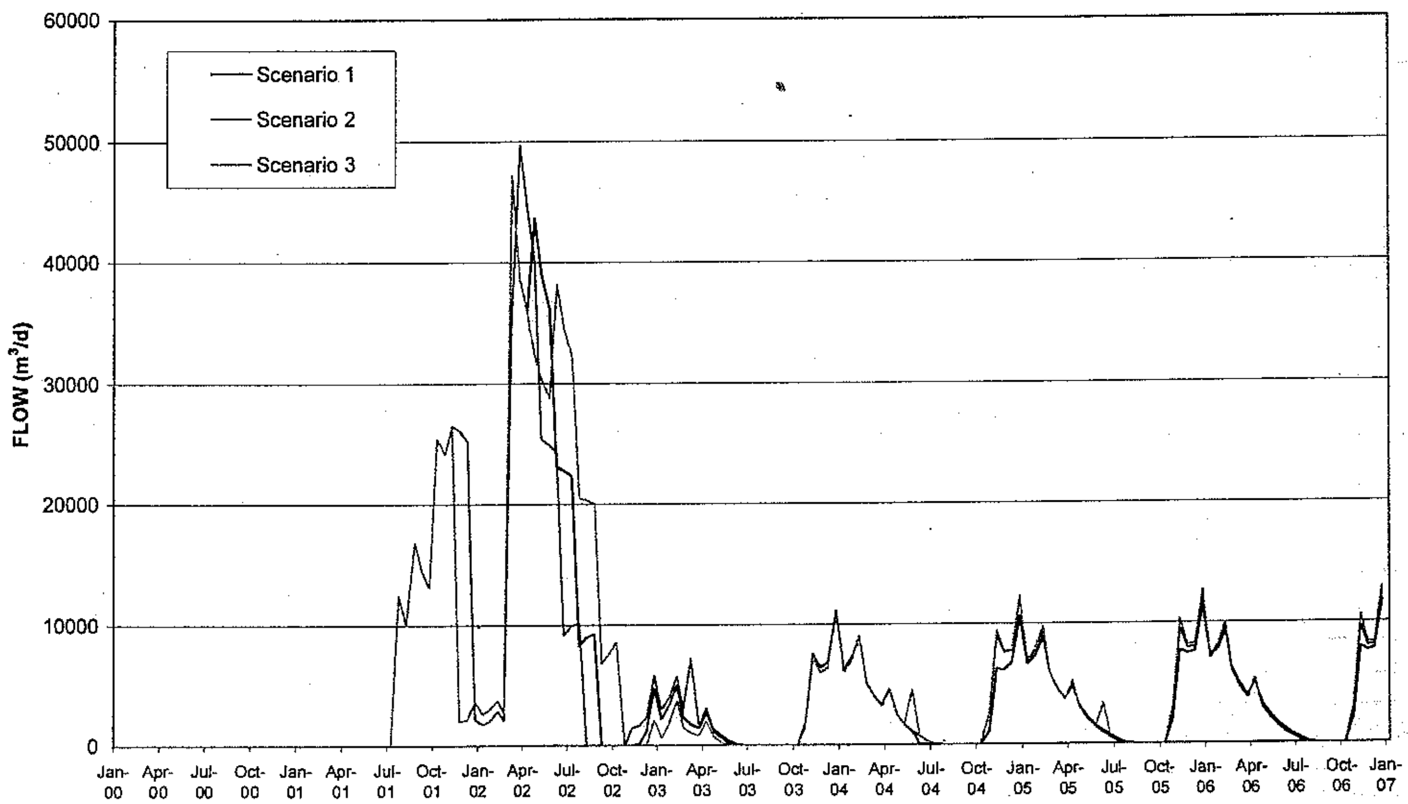


Figure 2.4 Predicted Flows from the Bypass Cutting During and After Construction

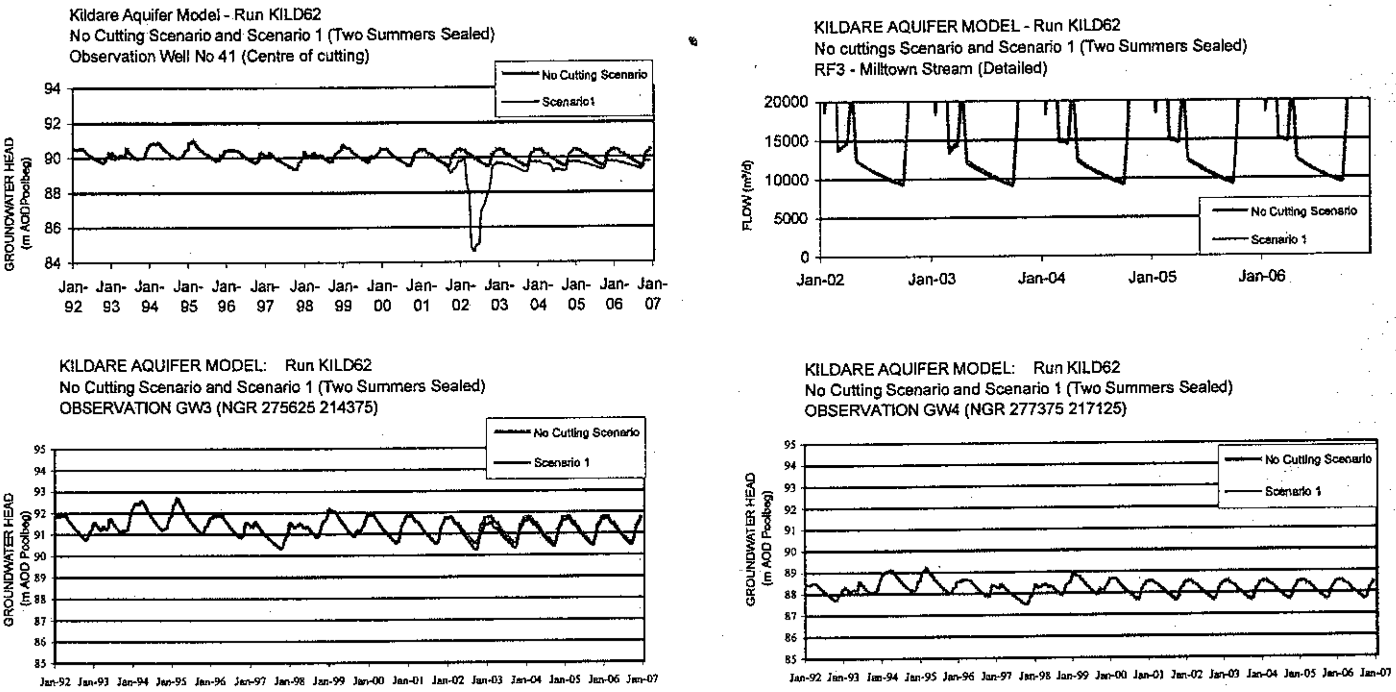


Figure 2.5 Impact Predictions

10. KTK Landfill - Investigations, Leachate Management and Groundwater Monitoring

Mark Heesom, KTK Landfill Ltd. and Geoff Parker, ERM Ltd.

KTK LANDFILL
INVESTIGATIONS, LEACHATE MANAGEMENT AND GROUNDWATER MONITORING

Mr. Mark Heesom, B.Sc., KTK Landfill Ltd.
and
Mr. Geoff Parker, M.E.Sc., Environment & Resource Management Ltd.

Abstract

This paper describes site investigations, leachate management practices and groundwater monitoring at KTK Landfill, Ireland's first private sector, commercial landfill licensed by the Environment Protection Agency.

The nature of the wastes accepted at KTK Landfill will result in a leachate composition that will vary significantly from that measured at MSW landfills. It is expected that leachate data collected at the site will be useful to engineers and scientists whilst planning and designing future landfills in Ireland and abroad.

In addition, groundwater quality at the site is influenced by the flow of groundwater from the partially unlined County Council Silliot Hill Landfill site. The natural course of this groundwater is under the KTK Landfill. Therefore baseline data gathered both prior to and after the opening of KTK Landfill at monitoring boreholes downgradient of the Silliot Hill Landfill and upgradient and downgradient of the KTK Landfill are reviewed in this paper.

1. INTRODUCTION

The KTK Landfill is located some 10 km southwest of the town of Naas in the townlands of Brownstown and Carnalway Co. Kildare. This Landfill facility is situated within a large sand and gravel pit that is actively being worked by KTK Sand Gravel Ltd. The concept of a Landfill facility stemmed from a requirement of the planning permission to prepare a proposal to restore the pit. Mr. Kevin Keenan the managing director of KTK Sand Gravel Ltd., and his consultants conceived the plan in July 1997. Planning and waste licence applications followed during 1998 after the preparation of development plans and an Environmental Impact Statement. In October 1998 planning permission was granted for the facility and in April 1999 the Environmental Protection Agency granted a Waste Licence. In June 1999, Celtic Waste Ltd acquired the facility. KTK Landfill Ltd., a 100% subsidiary of Celtic Waste operates the facility.

This facility is unique on a number of counts. Firstly, it was the first private sector commercial landfill facility licensed by the Environmental Protection Agency (EPA) (Waste Licence Register No. 81-1). Secondly landfill development and operations have been ongoing since August 1999 adjacent to and within the same pit where there have been intensive sand and gravel extraction and processing activities taking place. Thirdly, it is situated within an unusually thick deposit of sand and gravel, it is underlain by a sand and gravel aquifer and it is downgradient of the County Council partially lined Silliot Hill Landfill. Finally the landfill is licensed to accept only non-putrescible, non-hazardous commercial and industrial wastes. These aspects of the development and the site geology are interesting from engineering and scientific points of view for the following reasons:

- The facility was licensed in April 1999 by the EPA to comply with the then draft and now finalised EU containment requirements for a landfill. As such the engineering of the landfill includes a composite base and side slope liners and leachate collection and evacuation systems.

- The ongoing sand and gravel extraction and processing requirements have offered negatives and positives to the development. Negatives have related to some construction and development coordination challenges. The positives have been the ready supply of engineering materials such as drainage stone, glacial till overburden for lining systems and silt for base leveling during cell development and covering of wastes. In addition a spin off benefit has been the full-scale classroom that the 20 metre plus high pit faces have offered to young and old quaternary geologists.

- The sand and gravel aquifer beneath the facility appears to be an infilled deep valley that trends from Silliot Hill to the lowlands that lie south of the KTK site. The sand and gravel aquifer appears to be limited in areal extent. Groundwater flow is down the infilled valley and as such a leachate plume extends in a southerly direction from the Silliot Hill Landfill site under the KTK site. Monitoring of the aquifer beneath the lined KTK site will thus provide a good indication of the extent of attenuation of contaminants discharging from the unlined portion of the Silliot Hill site, the effectiveness of the restoration capping layers at the Silliot Hill site and any potential leaks from the KTK Landfill.

- The nature of the wastes that may be accepted i.e. virtually no putrescible waste will result in a leachate signature that is expected to be quite different to that measured at MSW landfills. The data collected from this site over the next five to ten years will be of interest to scientists and engineers involved in characterization and treatment of leachate as the implementation of the EU Landfill Directive will result in all new landfills having a smaller content of putrescible wastes.

It is not possible to deal with all of these aspects of the development and hydrogeology in this paper and thus in the spirit of the Seminar this year the paper focuses on the investigation, protection and monitoring of the sand and gravel aquifer which underlies the KTK and Silliot Hill sites.

2. SITE INVESTIGATIONS AND HYDROGEOLOGY

2.1 Site Investigations

Geological investigations have been carried out on the KTK site, on the adjoining Kildare County Council Silliot Hill Landfill site and the nearby Kilsaran Concrete site.

Since 1982 a considerable number of boreholes have been drilled on behalf of the County Council, Kilsaran Concrete and KTK since 1982, which have yielded a significant amount of data regarding the underlying geology and hydrogeology of the area. KTK Sand and Gravel carried out detailed hydrogeological investigations during 1997 prior to the various consent applications. Fourteen boreholes and five trial pits were dug in the latter half of 1997. Regular groundwater monitoring has been carried out since then. A number of these boreholes are currently still being used for groundwater monitoring purposes.

The geology and hydrogeology of the KTK site was investigated and described by K.T. Cullen & Co. Ltd., and S.M. Bennett & Co. Ltd in the 1998 Environmental Impact Statement Report and some text from that report follows.

2.2 Bedrock Geology

The distribution of bedrock geology of this area is illustrated in Sheet 16 of the 1:100,000 map series published by the Geological Survey of Ireland (GSI). The bedrock immediately beneath the site is described as calcareous greywacke, siltstone and shale. It is referred to as the Carrighill Formation. The Carrighill Formation is uppermost in the local succession known as the Kilcullen Group. The Kilcullen Group is Lower Paleozoic in age and generally recognised as Silurian (Llandovery - Ludlow). The Silurian depositional period occurred between 435 and 395 million years ago.

In the vicinity of the KTK site, the bedrock of the Carrighill Formation outcrops or is near surface in three areas: Delamain, Silliothill, and Brownstown (west). The Brownstown (west) exposure was a former slate quarry and the Delamain exposure was also a quarry.

Structurally the Kilcullen Group is heavily folded and the axes of these folds are aligned along the Caledonian trend (northeast - southwest). There is good topographic relief evident in the bedrock surface, which ranges in elevation from 132 mOD along the former N9 near Silliothill to less than 94 mOD beneath the KTK site. This relief may be related to a plunging fold structure.

2.3 Overburden Geology

The local quaternary deposits have been mapped by the Geological Survey of Ireland (GSI).

The KTK site is located on the southern flank of a flat-topped hill, which is approximately one kilometre in diameter. The overburden sequence in the vicinity of the KTK site is made up of strata of topsoil, silts and sands; clayey till; sand/gravel which in turn overlie the shale bedrock. None of the boreholes drilled on the KTK site reached the bedrock surface. BH 97-3d was drilled from the base of the pit. It was extended to the greatest depth on the site and was terminated at 94 mOD without striking bedrock. Therefore, there appears to be between 25 and 30 metres of glacial deposits underlying the floor of the pit, which is at approximately 118 to 120 mOD. The geological deposits of most significance are described below.

Upper Clayey Till

The upper clayey silt till, which is present below the topsoil on the higher ground, is composed of a variable mixture of clay and silt with sand, gravel and cobbles present. Generally the thickness of the capping layer decreases with increasing elevation. The till is thinnest on the north side of the site where in BH 97-10 it is found just below ground surface and is less than 1.5 m thick. At lower elevations and close to the marsh/stream south of the KTK Pit in the borehole adjacent to Chamney's Bog (97-7d) the till is underlain by 3.7 metres of younger sediments and the glacial till is approximately 14.4 metres thick. Thus sand and gravel deposit becomes confined by up to 18 metres of fine grained sediments south of the KTK Pit.

Sand and Gravel

The working faces of the existing pit show glacial sediments composed of a clayey silt till overlying fine interbedded sand and medium gravel. The underlying sand and gravel sediments contain sub-rounded clasts dominated by limestone lithologies. Calcretion occurs occasionally but is restricted to beds containing larger clasts. Sediments are well sorted and consist of alternating beds of fine sand and gravel with some near-homogeneous sediment units. Syndepositional and post-depositional deformation structures are evident in the exposures and the dip angles and orientation of stratification observed indicates that the depositional flow directions ranged between southeast and southwest.

The alternating horizontal units of planar-bedded sand and open-work gravel which are exposed in this pit are a common feature in subaqueous environments and are indicative of alternating periods of high and low sediment input and flow regimes.

Both ice proximal and ice distal environments are indicated by the sediments observed in the pit face and indicate glaciofluvial outwash deposition within a subaqueous environment. The types of deposits are referred to as Sandar deposits or outwash plateaux to indicate deposition in lowland areas in front of valley glaciers and ice sheets. The sediments also reflect frequent fluctuations in depositional flow velocities and sediment concentrations.

The original thickness of the sand and gravel deposit at the KTK site was in places in the range of 45 to 50m.

2.4 Hydrogeology

2.4.1 Climate

The long-term records of temperature, rainfall, and evapotranspiration compiled by the Meteorological Service characterise the climate of the area. In regard to the hydrogeology of the area the total and net rainfall are relevant.

Rainfall
The closest rainfall stations to the site with long-term records are located at Kilcullen Garda Station and Naas (Gowran Grange) and Ballymore Eustace. The average rainfall at these three stations is 883 mm per year. It is assumed that that this average is representative of the average rainfall at the KTK site. A rainfall gauge was established on the site late in 1999. The recorded rainfall at the site during 2000 was 882 mm.

Evapotranspiration
The average potential evapotranspiration (PE) is approximately 500 mm per year. The actual evapotranspiration is less than potential in the month of July as a result of moisture deficit in the soil accruing during the summer. The actual evapotranspiration for the year is estimated to be 480 mm.

Effective Rainfall
The effective rainfall is the total rainfall less the actual evapotranspiration. The average effective rainfall at the site is estimated to be approximately 400 mm per annum.

2.4.2 Conceptual Model

A conceptual model of the regional hydrogeology in the Silliothill/Brownstown/Carnalway was first presented in a 1983 Report by An Foras Forbartha (AFF). That conceptual model included a recharge zone on the high ground, which constitutes Silliot Hill, and a discharge zone at the toe of the so-called terminal moraine in which the KTK Pit is situated. An Foras Forbartha indicated that the major local discharge zone for recharge in the area is Canon's Bog with a smaller component of recharge, from the eastern boundary of the catchment, flowing in the sands and gravel towards Chamney's Bog.

Figure 3.5.1 included in the 1998 EIS illustrated a conceptualised representation of the groundwater flow regime in the Silliothill/Brownstown/Carnalway. The Silliot Hill Landfill site and the KTK Site are located within a local groundwater catchment of the River Liffey, which also includes Cannon's Bog and Chamney's Bog. The precise limits of the local catchment are unconfirmed as there are no strategically placed regional boreholes. The indicated local groundwater catchment was delineated on the basis of topographic data and the results of the localized drilling programmes.

The existing body of data does not invalidate the original AFF conceptual model However, the extent of discharge into Cannon's and Chamney's Bogs may be less than what AFF envisaged, given the thickness of the glacial till that was found overlying the more permeable glacial sands and gravel along the northern margin of bog/wetland area which lies to the south of the KTK Pit. It is possible that the bog/wetland is also associated with perched groundwater in shallow glacial deposits, which are underlain by low permeability glacial till in this area of low topographic relief that extends to the River Liffey. Detailed geological and hydrogeological data are not available for the Cannon's Bog area or the area lying south of county road PI 321 and north of the River Liffey.

The inference from the results of the site investigations is that groundwater, flowing in the glacial sand and gravel deposit, discharges via upward hydraulic gradients through a low permeability glacial till into Cannon's Bog and also the River Liffey via a horizontal hydraulic gradient that may be computed from the groundwater levels determined in the Silliot Hill Landfill site monitoring boreholes (i.e. BH1) and the closest well to the Liffey (i.e. domestic well D10).

2.4.3 Characteristics of Sand and Gravel Deposit

Thickness
The borehole logs suggest that at least approximately 26 metres of sand and gravel underlies the base of the KTK Landfill in some areas (approximately 118 to 120 mOD). The field evidence indicates that the majority of this succession is composed of inter layered sand and gravel. However, some of the borehole logs suggest the sand and gravel grades with depth to a gravel in a clayey matrix. For the purposes of this hydrogeological assessment all of the glacial deposits that underlie the clayey glacial till were considered to be one hydrostratigraphic unit. Bedrock underlies this unit.

Permeability

Given the heterogeneous nature of the sand and gravel deposit the measured co-efficient of permeability is expected vary over 2 to 3 orders of magnitude. Pumping tests, laboratory permeability and rising head tests have been carried out on the sand and gravel deposits. There is a wide scatter in the K values estimated from the test data with computed values between 1.3 x 10^{-3} to 1.1 x 10^{-5} m /sec. The probable range in a representative K value for the glacial sand and gravel deposit is 10^{-4} to 10^{-5} m/sec.

Groundwater Levels

Logs for some of the County Council boreholes (i.e. BH4, BH5, BH11s and BH11d) indicated discontinuous layers of silt and layers of gravel in a clayey matrix within the sand and gravel deposit. These may give rise to local hydraulic discontinuities. However, in regional terms, the saturated sand and gravel deposit is considered to be a single hydraulic unit.

The water table/piezometric level in the sand and gravel deposit underlying the KTK site ranges from approximately 116 mOD to 118 mOD. This indicates that the water table lies from 2 to 3 m below the base of the Pit and therefore there are at least 20 metres of saturated sand and gravel overlying the bedrock. Seasonal fluctuations of between 1 and 1.5 m. have been observed in these glacial sediments.

Gradients

The results of water level monitoring within and in the environs of the site indicate a complex picture. Inspection of water levels in BH1 and BH97-5d suggest a relatively gentle slope to the water table/piezometric surface in the sand and gravel deposit with a hydraulic gradient from north to south of the order of 0.001. However, between some boreholes steeper gradients have been computed. The hydraulic gradient between BH1 and D10 is in the order of 0.003.

Historically downward vertical hydraulic gradients have been observed beneath the site through the sand and gravel deposit.

Historically there have been upward vertical hydraulic gradients through the confining layer of clayey till downgradient (south) of the KTK Landfill.

Groundwater Flow

Groundwater movement in the sand and gravel deposits beneath the KTK site is likely influenced by the River Liffey. However, there are only a few regional monitoring boreholes available suggesting that groundwater flows from Silliothill/Brownstown towards the Liffey in a southerly or south-southwesterly direction. There is strong evidence to suggest groundwater discharge into Cannon's Bog. These include springs, rises and artesian/subartesian conditions at some of the monitoring borehole nests.

The banks of the Liffey were examined between the West Drain and Chamney's Bog Stream to determine the nature of the geology in this area. The banks are steep and high (at least 10 m in some places) suggesting unsaturated sand and gravel deposits. There were no signs of ground water flow from the banks. Therefore, it is inferred that the water table along the banks is controlled by the Liffey water level.

Estimates of groundwater flow and velocity have been made using Darcy's law:

Q = K i A

Q = flow quantity (m3/sec)

K = hydraulic conductivity (m/sec); representative range = 10^{-4} to 10^{-5} m/sec.

i = head difference/ length of flow path two measurements: 0.001 and 0.0035

A = cross-sectional area of flow (m^2); variable and not defined in detail

From the above it is obvious that the flow calculation will produce at best a probable range in flow rather than a unique value.

The saturated thickness is not defined everywhere beneath the site. However a reasonable assumption is an average of 20 m. The groundwater level trend lines make a simple calculation difficult since over part of the site the hydraulic gradient is much steeper. If the flow width is assumed to be 550 metres, the width of the site along the northern boundary road PI 318, then a calculation of the range in flow may be performed.

Calculations using different combinations of the parameters suggest that the likely flow beneath the site is in the range of 10 to 100 m^3/day or approximately 3,600 to 36,000m^3/year.

Vulnerability of Sand and Gravel Deposit
The sand and gravel deposits beneath the base of the sand and gravel pit are highly vulnerable to pollution from surface sources. The design of the KTK Landfill includes construction of a composite lining system in accordance with guidelines set out by the EU and the EPA. In this case the sand and gravel deposit will have a low vulnerability to pollution.

Groundwater Use
Enquiries were made in March 1998 at a number of residents to establish groundwater use downgradient of the KTK Site and along road PI 321. The enquiries revealed that only well D10 is being used for livestock watering.

3. LEACHATE MANAGEMENT

3.1 Site Design

In line with the EU Landfill Directive the site is designed as a total containment facility.

The facility is lined using a composite lining system. The basal lining system comprises a minimum of 1 metre of compacted clay/silt till (with a maximum permeability of $1x10^{-9}$ ms^{-1}); overlain with a 2mm High Density Polyethylene (HDPE) liner. This lining system also extends along the southern slopes of Phase 1, which are graded at a slope of 1:3.

The lining system for the other steeper slopes in the site comprises a protective layer of non-woven geo-textile (1200 g/m^2), overlain by a reinforced geo-synthetic clay liner (GCL) and finally a 2mm HDPE geomembrane.

The basal clay liner extends up the sidewall slopes by up to 2.5 metres providing additional leak protection.

The basal liner system is overlain with a protective non-woven geo-textile (1200 g/m^2) and a minimum 500mm depth of rounded no fines 40mm pebble (clause 505 drainage stone). Perforated drainage pipes are placed within the 500mm drainage layer.

The site will comprise 5 develoment phases, which allow for the existing sand and gravel operation to continue whilst landfilling operations are undertaken. At present, Phases 1, 2 and 3 have been constructed, with waste currently having been deposited in Phases 1 and 2 to pre-settlement levels (an average depth of between 10 and 22 metres). Landfilling operations in Phase 3 have just commenced.

3.2 Leachate Management

Leachate is completely contained within the above lining system with a maximum allowable head of 1 metre at any point above the HDPE liner (waste licence condition 4.15.2). As the site is constructed with a cross fall of 1/100 to allow for drainage to the collection sumps this means that in practice, approximately half of the basal HDPE will have a zero head of leachate at any time.

Leachate head is monitored using a real time system of vibrating wire piezometers (VWP) located at 7 points within the body of the landfill (an additional VWP is located within the leachate holding tank).

The leachate collection system comprises a network of perforated drainage pipes placed within the 500mm of drainage stone overlying the basal liner. A network of 100mm diameter branch collection pipes feed the main 225mm diameter trunk pipe.

Phases 1 and 2 drain to one leachate collection sump from which leachate is pumped using two inclined riser borehole pumps to a leachate holding tank located adjacent to the landfill area. Phases 3, 4 and 5 will drain to a second sump, which will also have two inclined risers. The leachate may be pumped from the leachate holding tank into a road tanker for transfer to the local treatment works at Athy or to the foul sewer in Kilcullen.

An alternative management method was introduced in September 2000, which allows for the leachate to be pumped from the leachate holding tank onto the site and re-circulated through the body of the waste.

The re-circulation allows for faster stabilisation of the emplaced waste by increasing its moisture content. The wastes received at KTK Landfill generally have a very low moisture content compared to typical municipal wastes. The increased moisture levels encourage faster biological and mechanical stabilisation. Any leachate remaining after re-circulation is collected and taken to Athy for biological treatment.

4. GROUNDWATER MONITORING

4.1 Context

The KTK Landfill is situated within a hydrostratigraphic unit that consists of unsaturated and saturated sand and gravel deposits. The total thickness and saturated thickness maxima are approximately 50 and 26 metres, respectively. Groundwater, which potentially could be impacted by the proposed KTK Landfill, moves through the saturated zone of this unit beneath the KTK Pit. The location of the KTK Landfill is adjacent and hydraulically downgradient of an existing landfill which occupies the same hydrostratigraphic unit. In consideration of these factors groundwater quality within the saturated zone of this hydrostratigraphic unit was examined during the facility application phases over five general areas:

- upgradient of the existing County Council landfill;
- immediately upgradient of the KTK site;
- beneath the KTK site;
- immediately downgradient of the KTK site;
- at a further distance downgradient from the KTK site.

The Waste Licence requires quarterly monitoring of groundwater. The focus of the monitoring programme at the KTK Landfill has been boreholes installed on the KTK site within the underlying sand and gravel aquifer.

The current groundwater monitoring regime of the KTK Landfill includes four (4 No.) boreholes immediately downgradient of the Silliot Hill Landfill and thirteen(13 No.) boreholes downgradient of the KTK Landfill. Private domestic wells that are located within 500m of the site are also monitored annually.

Groundwater samples are analysed for the standard EPA suite of parameters for landfills. Once a year the samples are analysed for List I/II organic parameters.

A large water quality data base exists and is growing. The data are presented in quarterly reports in spread sheets and are graphically presented against time to allow visual inspection of the data trends. Some of the data trends are highlighted below.

4.2 Groundwater Quality Immediately Upgradient of the KTK Site

It is recognised that groundwater flowing beneath the KTK Landfill from the north has passed beneath the existing unlined part of the Silliot Hill Landfill. Borehole BH-4 was installed in 1983 on the northern boundary of the KTK Site and lies downgradient of the Silliot Hill Landfill.

Historically groundwater quality in BH-4 has been regularly monitored since 1991 and it is evident from the analyses that groundwater quality is well below that expected for the area due to the MSW landfill. In the period prior to the opening of KTK Landfill, in December 1999, conductivity levels recorded for BH-4 had increased steadily from 1273 µS/cm (27/03/91) to 3940 µS/cm (23/11/99). Since 1999, conductivity readings have fluctuated in and around the higher level finally dropping to 2540 µS/cm on 09/05/01.

Ammoniacal Nitrogen and chloride concentrations also increased considerably in the same 1991 – 1999 time period from 0 mg/l to 154 mg/l and 129.9 mg/l to 636 mg/l respectively. Again, since 1999 ammoniacal nitrogen concentrations have fluctuated and now lie at 134 mg/l (09/05/01). Chloride however, reached a peak of 748 mg/l on 06/03/01 and has since dropped to 295 mg/l (09/05/01), respectively.

KTK-16 was installed in 1999 close to BH-4 but at a shallower depth. It has been monitored since 1999. Conductivity levels have consistently risen from 4540 µS/cm on 06/12/99 to 9050 µS/cm on 09/05/01. Chloride levels reached a peak of 1369 mg/l on 17/05/01 but have since decreased gradually to 887 mg/l as recorded on 09/05/01. Ammoniacal Nitrogen concentrations have also increased from 234 mg/l (6/12/99) to 516 mg/l (09/05/01) as reported for the second quarter, 2001.

4.3 Groundwater Quality Downgradient of the KTK Site

BH-5 has been monitored since 1991 and has also exhibited increases in conductivity from 583 µS/cm (27/03/91). This level peaked at 837 µS/cm on 04/12/97 and has since dropped off to 291 µS/cm as observed on 22/11/00. Chloride and ammoniacal nitrogen concentrations also peaked on 04/12/97 with concentrations of 85 mg/l and 2.47 mg/l respectively. Again these concentrations decreased to 10.97 mg/l and 0.3 mg/l as reported in the final quarter of 2000. This borehole has not been sampled since 22/11/00 as it was damaged.

Other downgradient monitoring boreholes are 97-5d, 97-6d and 97-7d. These have been monitored regularly since the end of 1997. Conductivity has decreased at these three points in the period from 04/12/97 to 09/05/01 from 720 to 705 µS/cm, 826 to 686 µS/cm and 711 to 603 µS/cm respectively. There has been very little change in chloride concentrations, which still remain well below the MAC at 50 mg/l, 52 mg/l and 16 mg/l respectively. Ammoniacal nitrogen has increased slightly at all three locations since monitoring commenced. Prior to the opening of KTK Landfill in December 1999 ammoniacal nitrogen concentrations were 0.2 mg/l, 0.1 mg/l and 0.1 mg/l at 97-5d, 97-6d and 97-7d respectively. Since 1999, concentrations have fluctuated marginally at all three locations and currently still remain below the MAC at 0.2 mg/l, <0.2 mg/l and <0.2 mg/l respectively.

4.4 Observations on the Groundwater Quality Data Base

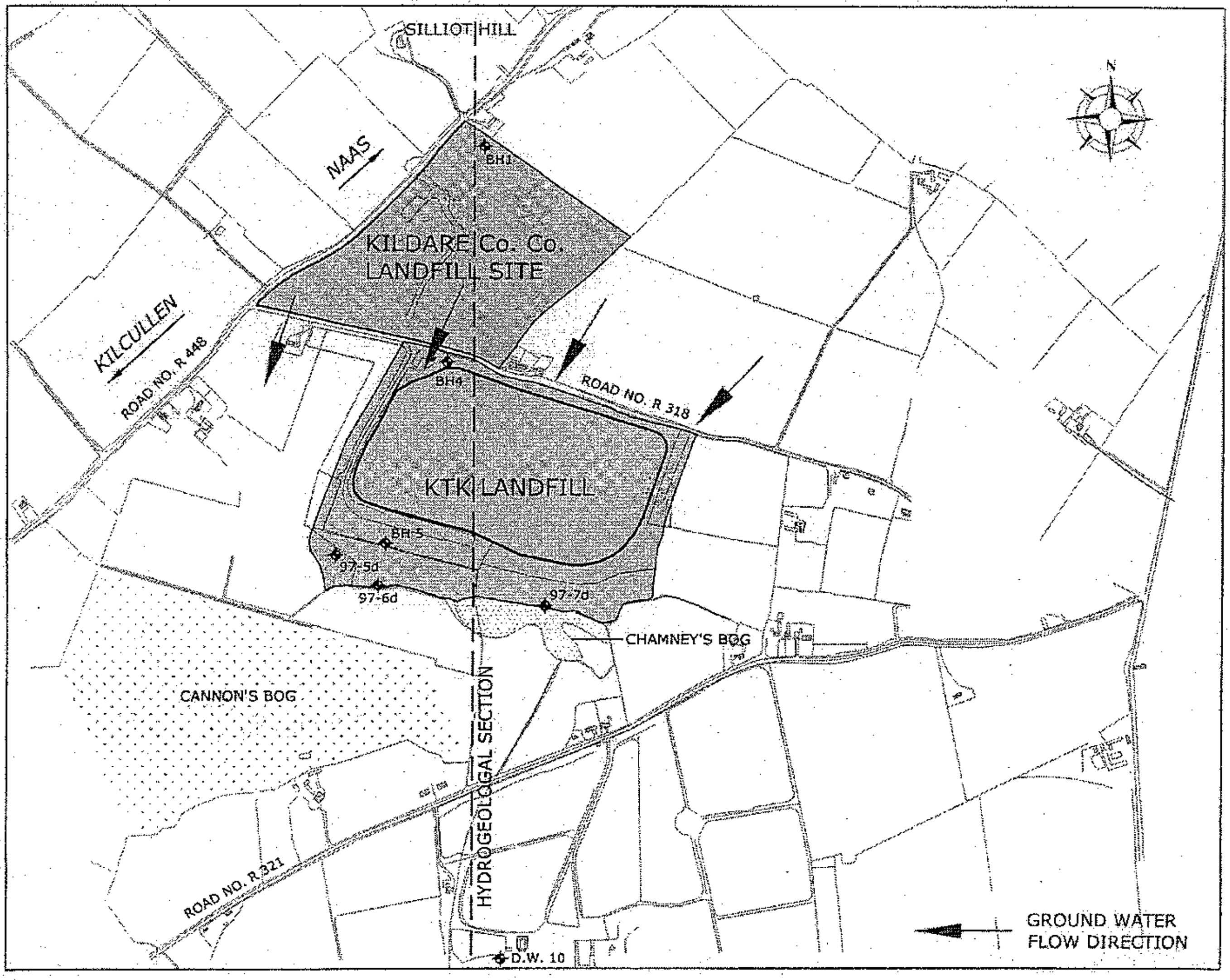
Some preliminary observations on the data in relation to the hydrogeology of the area:

- Only the western part of the site appears to be beneath the core of the leachate plume from the Silliot Hill Landfill.
- Attenuation mechanisms appear to be at work in the aquifer as the ammoniacal nitrogen concentration diminishes significantly along the 350m plus flow path

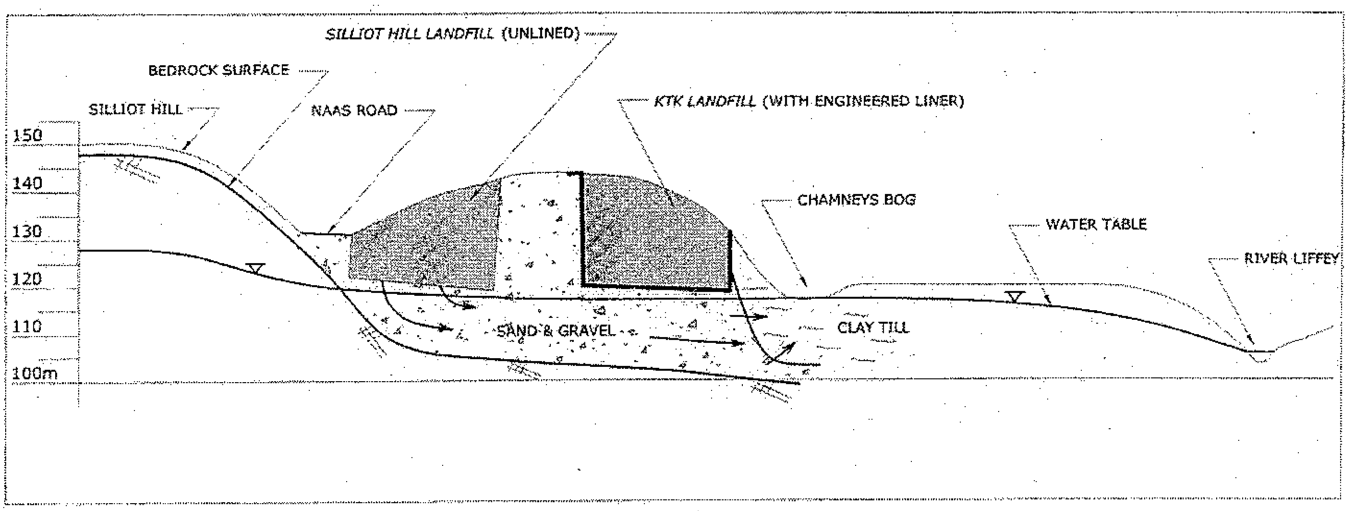
- The mass of contaminants entering the groundwater flow system may be decreasing as Kildare County Council reduces the amount of infiltration through the unlined portion of its landfill site.

- Additional boreholes would be worthwhile from a research standpoint to map groundwater quality in the aquifer to the west and south of the KTK site.

- The historical analytical data for the leachate from the Silliot Hill Landfill coupled with the analytical data from the downgradient monitoring borehole network would be useful in relation to assessing advection and diffusion in this sand and gravel aquifer. Diffusion of the conservative parameter chloride is apparent from the monitoring data upgradient and downgradient of the KTK Landfill. Depending on the actual contaminant transport mechanism and the characteristics of the contaminant source it is possible higher concentrations of chloride would be measured in monitoring boreholes downgradient of the KTK Landfill as historical or future contaminant releases from the unlined part of Silliot Hill landfill migrate downgradient.



SITE LOCALITY PLAN



CONCEPTUAL MODEL - HYDROGEOLOGAL SETTING OF THE KTK LANDFILL

11. Contamination & Remediation in Gravels – Sir John Rogerson's Quay Gasworks Dublin

Mark Adamson, Environmental Engineer, Parkman UK.

CONTAMINATION AND REMEDIATION IN GRAVELS – SIR JOHN ROGERSON'S QUAY GASWORKS DUBLIN

Mark Adamson – Parkman Environment

Abstract

The former gasworks at Sir John Rogerson's Quay is currently being remediated to prevent further contamination of a gravel aquifer and facilitate the redevelopment of the site. The site and gravel aquifer beneath have become contaminated with by-products from coal gas production. The most significant contaminants were PAHs, phenols, heavy metals and cyanide. Remediation goals were established using quantified risk assessment techniques based on data from 4 intrusive site investigations. All available remediation techniques were considered in the design of the remediation scheme including ex-situ treatment by gravel washing, vibration screening, thermal desorption and physio-chemical soilwashing. These four techniques were selected as most appropriate given the short timescale required, the granular nature of the soil and the complex mixture of contaminants. Gravel washing and vibration screening were undertaken on site, whilst soil was transported to mainland Europe for thermal desorption and soilwashing. The project required a Waste Management Licence as hazardous waste was treated and recovered on site for disposal abroad. The licence was regulated by the Irish Environmental Protection Agency and ensured appropriate measures were taken to protect the local environment during the course of the works. In order to control groundwater in the excavations a cut-off wall was constructed around the site perimeter using a bentonite-cement slurry.

1. INTRODUCTION

1.1 SITE DESCRIPTION

The Sir John Rogerson's Quay Gasworks site with a total area of 8.9 hectares is located approximately 1.5km to the east of the city centre adjacent to the south bank of the River Liffey. Beyond the adjacent roads the site is bounded to the south by residential and commercial properties, to the west by warehouses / depots, to the east by Grand Canal Dock and to the north by the River Liffey.

Geology, Hydrology and Hydrogeology

Historically the site was reclaimed from the southern flank of the Liffey Estuary in Dublin bay. A substantial amount of filling was required to reclaim the site from the estuary, resulting in the layers of fill now present. The near surface geology underlying the fill is made up of alluvial deposits consisting of interbedded silts and sands, underlain by glacially deposited gravels and boulder clays over a limestone bedrock. The hydrogeological conditions pertaining to the site are best considered in terms of the two principal water bearing horizons, as discussed in the following paragraphs.

The general geology of the site comprises Fill of low to moderate permeability, overlying Estuarine Alluvium consisting of clays, silts and sands that have a limited permeability. These in turn overlie the glacio/fluvio-glacial gravels that have a moderate to high permeability ($1x10^{-4}$ m/s). On a small scale, the made ground, alluvium and gravels may have a complex interrelationship of different permeabilities, flow directions and perched water levels. On a larger scale, it is reasonable to consider the fill, alluvium and gravels as a single unit, comprising an aquifer that is in hydraulic continuity with the rivers. Groundwater flow is likely to be most copious within the gravels and would tend to be towards the rivers. Boulder Clay underlies the glacial gravels and in general serves as a groundwater partition between the gravel aquifer and limestone aquifer beneath. The Carboniferous 'Calp' Limestone, which underlies the site at depth, is informally considered a "Minor Aquifer" by the Geological Survey of Ireland.

1.2 SITE HISTORY AND CONTAMINATION

The principal historical use of the site was gas production by the process of coal carbonisation. This activity operated from the early 1800's to the 1970's and a complicated history of expansion and reorganisation is observed in the historical records.

Contamination sources on the site were associated with general fill, purifier sheds, and buried / above ground tanks. Purifier sheds produced spent iron oxide waste and this was used for general filling at various locations over the site. These areas have associated cyanide and sulphate contamination. Clinker and ash from the retort houses were found in the fill material at various locations and were a source of heavy metal contamination. All of the above ground tanks on the site had been demolished except one and this had been cleaned out prior to the start of the project. However many buried tanks remained (4 No. over 20m in diameter) containing demolition rubble and liquid coal tar. All of the buried tanks were constructed with cast iron walls and a puddle clay base. Coal tar contamination was invariably encountered in the vicinity of these tanks due to leaks and spillages.

After investigating the site, it was clear that the general fill was often contaminated with some or all of the contaminants mentioned above, whilst the natural strata beneath were only effected by the mobile components. Ammonia, polycyclic aromatic hydrocarbons (PAHs), phenols and sulphates have impregnated the natural strata, introduced by groundwater flow. As the gravel was the stratum with the highest permeability, mobile contaminants tended to be concentrated there. Some gravels were so saturated with oil and tar, particularly at the gravel / clay interface that they were considered a contamination source in their own right.

2. REMEDIATION STRATEGY

2.1 RISK ASSESSMENT

Quantified Risk Assessment (QRA) has been adopted by the Irish Environmental Protection Agency and used in conjunction with generic guidelines (such as Dutch Intervention Values) where applicable. The remediation goals for the Sir John Rogerson's Quay gasworks were derived from QRA. The assessment was made using internationally accepted methods (predominantly USEPA guidelines) and Site Action Values (SAV's) based on the risks to both groundwater and human health were established. The groundwater risk assessment assumed that the water beneath the site would remain in continuity with the gravel aquifer and the rivers. In reality, the groundwater is sealed off by an underground cut-off wall, which makes the assessment more conservative.

2.2 REMEDIATION TECHNOLOGY OPTIONS

Removal to Landfill

Many similar sites in Northern Ireland and the rest of the UK have been remediated by excavating the contaminated soil and removing it to landfill. The benefits of this approach include relatively low costs (landfill tax exemptions are often applicable), speedy delivery of a clean site and simple execution. Removal to local landfill was not an option for the Dublin project as there were no suitably licensed landfills in the Republic of Ireland. Therefore, a 'dig and dump' approach was rejected.

Bioremediation

Bioremediation refers to the use of microbes to breakdown contamination into inert waste products (e.g. CO_2 and H_2O). These microorganisms are sometimes artificially introduced to the contaminated soil, but more commonly air and nutrients are added to encourage the proliferation of microbes already present. These techniques are relatively inexpensive, sustainable, and have proven successful on many remediation projects.

The main disadvantage of bioremediation techniques, when applied to gasworks, is that the microbes do not thrive in the presence of cyanides[4] and cannot break down the longer hydrocarbon chains of coal tars. The complex mixture of contaminants (heavy metals, hydrocarbons and cyanides) encountered on the gasworks precludes the successful use of biological remediation techniques. Bioremediation is also a relatively slow process and would not have been able to achieve the remediation goals in the timescale required by the client.

In-situ Stabilisation / Containment

This technology isolates contamination from the surrounding environment by stabilising or 'freezing' it in place, often by mixing the soil with cement. The benefits include its suitability for all soil and contamination types as well as minimal local environmental impact during execution as little soil is exported from the site. However, the contamination, albeit isolated, remains on the site and this method was rejected, as questions would inevitably have been asked by funders and prospective developers about the reliance upon containment measures whose life was not infinite.

Thermal Desorption

Thermal desorption is an ex-situ soil treatment involving the removal of contaminants unstable at high temperatures by heating the soil in a closed furnace. Fumes arising from the oven are then rigorously treated in order to meet stringent air emission criteria. The method is well suited to the granular soils encountered beneath the site and is capable of successfully treating the tar-saturated soils associated with former tar tanks.

Disadvantages of this method are the relatively high costs (soil was transported to Holland as no such facilities exist in Ireland), and limitations based on sulphate and heavy metal concentrations. Thermal desorption was chosen as one of the treatment methods as it would be able to treat soil too contaminated with heavy tars for soilwashing.

Physio-chemical Soilwashing

Soilwashing is an ex-situ technique developed from the mineral extraction industry. The method assumes contamination is concentrated in a certain soil fraction and endeavours to extract this 'dirty' fraction from an otherwise 'clean' soil matrix. Once extracted, the dirty fraction is normally disposed to landfill while the clean fraction is recycled in construction projects. The method only becomes economic when the recovered clean material significantly outweighs the contaminated material extracted. It is not possible to wash clay soils successfully, whereas gravel washes very well.

In the soils excavated at Sir John Rogerson's Quay, contamination was generally confined to the particles less than 5mm and as the majority of the made ground and contaminated natural deposits were granular, the soil lent itself to this type of treatment. As this was an ex-situ treatment, remediation would be possible in the 18-month timescale required and soilwashing was adopted as the main treatment method. In the design of the project, it was envisaged that a mobile soil washing plant would be used to remediate the gravels and other suitable materials from the gasworks on site. However, it became clear that a long public consultation period would have been necessary before the plant could be licensed and commercial pressures to develop the site precluded this kind of delay.

2.3 WASTE LICENCING

General

Under the Waste Management Act 1996, Section 39, the recovery of waste at a facility is not permitted save under a Waste Licence[5]. Various recovery processes (discussed below) were employed on the gasworks to ensure that clean material was not exported for treatment and therefore it was necessary to operate the site under a Waste Licence. An application was made to the Irish Environmental Protection Agency (EPA) in July 1999, supported by a quantified risk assessment. The application was successful and in 27th August 1999, the first Waste Licence for an Irish remediation project was issued to Dublin Docklands Development Authority (DDDA). The DDDA commissioned Parkman as Environmental Consultants to manage the licence and oversee the remediation. The licensed activities, in accordance with the Fourth Schedule of the Waste Management Act[5], 1996 were:

- Class 2: Recycling or reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes).
- Class 4: Recycling or reclamation of other inorganic materials.

Before waste activities could begin, a detailed Environmental Management System (EMS) was submitted to the EPA[3]. The EMS included method statements for all aspects of the works, and these were agreed with the EPA Inspectors.

Movement of Materials

Classification, identification and control of excavated soil were paramount to the success of the project. Visual assessment of contaminated soils was unreliable and in all cases, soil was assessed using chemical analysis. The site was split into 20m by 20m by 1m cells and each cell was assessed individually, with the exception of buried tanks, which were considered as a whole. In order to characterise each cell, samples were taken and dispatched for laboratory analysis in accordance with the British Gas Specification (ver. 2.3)[1].

The waste licence conditions stipulated that all wastes leaving the facility were weighed and the destination, waste description and carrier details noted. Soil was removed from the facility either by road or by ship via an overhead conveyor. The conditions were met using a calibrated weighbridge for road transport and a weigh-cell incorporated into the conveyor. All waste exported to mainland Europe for treatment was subject to a Transfrontier Shipment Notice and the DDDA were required to put up a financial bond to cover treatment of the soil in the event that it was not accepted abroad.

Environmental Monitoring

The waste licence required that the remediation works be undertaken without significant impact on the local environment and emissions to air, sewers and groundwater were monitored to ensure compliance.

Emissions to air comprised, dust, vapours and noise. Any excavation in dry weather has the potential to produce dusty conditions, but monitoring dust concentrations was particularly important during the remediation as the soil had the potential to produce hazardous dust. However, occupational health and safety monitoring and ambient monitoring of PM_{10} dust particles (particles 10 microns and smaller) indicated no such hazard had arisen.

The excavation of soil contaminated with volatile compounds also has the potential to produce harmful concentrations of those compounds in the air, particularly in deep excavations where vapours are seeping from their base and walls. The concentrations of these volatiles were monitored, on site, at the site perimeter and at ambient locations downwind of operations. Harmful concentrations were not detected outside the site at any time.

Groundwater quality in both the gravel and limestone aquifers beneath the site will be monitored once the remediation earthworks are complete. The purpose of the monitoring will be to demonstrate that the facility no longer represents a risk to the environment.

Surrender of the Licence

The waste licence can only be surrendered once the waste activities have been completed and the EPA is satisfied that the site is no longer having an impact on the local environment. A comprehensive Validation Report will be submitted to the EPA describing the works carried out, including the results of all environmental monitoring and soil analysis. The licence surrender will be an important signal for investors in the site that the remediation was carried out satisfactorily.

2.4 ENGINEERING CONSIDERATIONS

Bentonite Wall

In order to remove contaminated gravels for treatment the excavations extended down to 6 metres below the existing ground level and 4 metres below the mean water table in places. To facilitate the excavations an underground cut-off wall was constructed around the perimeter of the main site. The wall was 1020m in length with depths ranging from -3m AOD to -8.5m AOD. The most significant risk associated with this containment retaining wall was the potential for contaminated ground water and leachates penetrating the site following remediation. The wall had to have low permeability ($1x10^{-8}$ m/sec), a high degree of construction certainty and be capable of withstanding the bending moments and shear forces associated with cantilever retained heights of up to 5.0m. The chosen hybrid solution consisted of a slurry trench with CFA piles to provide the structural capacity[2].

3. REMEDIATION & RECOVERY OF GRAVELS

3.1 INTRODUCTION

The main objectives of this project were to remove contamination sources from above and within the gravel aquifer and protect the cleaned site in order that it could be developed without risk to the end users and surrounding environment. In order to achieve this economically, gravel was excavated and much of it was treated at Sir John Rogerson's Quay. The gravels are ideal for recovery as a large proportion (60 to 80%, see Fig 3.1.1) comprises the >5mm fraction. In the contaminated gravels, this coarse fraction is intrinsically clean and oily/tarry residues only cling to the surface. The washing process was designed to remove this surface contamination. Due to their large surface area to volume ratio the coarse gravel particles (40-100mm) are the cleanest, while the finer fraction (<5mm), with the smaller surface area to volume ratio is the most contaminated (see Fig 3.3.1 below). In order to recover the coarse and intermediate gravel fractions various processes were used, both domestically on site in Ireland and overseas in Belgium and Holland. The following sections describe the four methods used: Gravel washing, vibration screening, physio-chemical washing and thermal desorption.

3.2 ON-SITE GRAVEL WASHING

The washing plant comprised a loading hopper, 150mm screen, delivery conveyor, rotating drum with high-pressure water jets, silt/water collection hopper and sedimentation lagoons. Gravels identified as contaminated and containing a suitably large size fraction >5mm, were excavated and stockpiled adjacent to the plant. Once a sufficient quantity had accumulated, a loading shovel filled the input hopper and boulders larger than 150mm diameter were rejected by the screen. The particle fraction <150mm was then transported up an inclined conveyor and delivered into the wash drum. The drum was perforated to allow silt, sand and gravel <5mm to be washed out whilst the >5mm gravel and cobbles are retained inside. Gravels were moved through the rotating drum by spiral flights using the same principle as an Archimedes Screw. During its residence in the drum, the gravel was sprayed by high-pressure water jets and agitated by the drum's rotation. It is the action of the water and attrition of the gravel particles against each other that removes the surface contamination. Essentially contamination is taken from the soil phase and suspended/dissolved in the water phase.

Water, sand and silt were collected by a hopper positioned below the drum and this drained to a series of settlement lagoons. Once the sediments had settled out the wash water was pumped to a treatment installation on-site. The water was then discharged to foul sewer under licence, but could potentially be recycled back into the gravel washing plant. Clean gravel was discharged from the end of the drum onto a stockpile via an inclined chute.

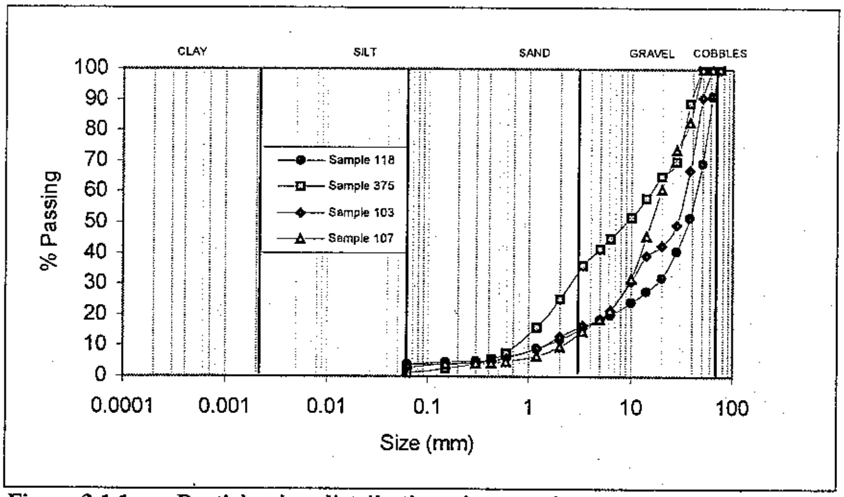


Figure 3.1.1 **Particle size distributions in gravel samples taken from Sir John Rogerson's Quay. Between 60 and 80% of the soil particles were 5mm or larger and suitable for recovery on site.**

Between 60 to 80% of the gravel was retained in the drum and could be re-cycled as backfill on the site. However, as there was a surplus of backfill on the site alternative destinations were sought in conjunction with the Contractor and the EPA. Washed gravels were tested and it was found that the contamination had reduced to below Dutch Intervention Values. It was found that material of this standard was readily marketable and a number of local outlets were found. Contaminated sand and silts from the settlement lagoons were dried and exported for treatment by either thermal desorption or physio-chemical washing depending on the grading and concentration of hydrocarbon contamination.

3.3 ON-SITE VIBRATION SCREENING

The settlement stage of the on-site gravels washing was time-consuming and trials were conducted to establish whether the contaminated fine fraction could be removed from the gravels using screening plant. A 'Viper 301 Turbo' 4-way screening plant was employed to split the gravels into four size fractions using one static (100mm) and 2 vibrating meshes (5mm and 40mm). The gravels were predominantly contaminated with PAHs and Fig 3.3.1. below summarises the results of the gravel screening trials. The initial objective was to improve the quality of the gravels so that they met Site Action Values and could be used for backfilling.

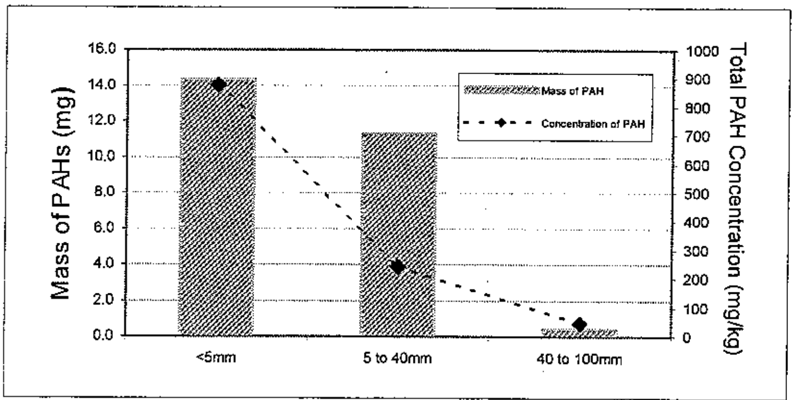


Figure 3.3.1. **Distribution of total PAHs in gravel by mass and concentration. PAHs are concentrated in the <5mm fraction.**

The trials were very encouraging with only the fine fraction remaining unsuitable for backfilling the site. The 5 to 40mm, and 40 to 100mm fractions were successfully processed to achieve soil concentrations below Dutch Intervention Values (40 mg/kg PAH). Occasionally when the gravel was particularly wet or tarry (as in Fig 3.3.1) some particles <5mm adhered to larger ones and it was necessary to screen the 5 to 40mm fraction twice before a concentration of <40 mg/kg total PAH was achieved. These recovered gravels were then recycled in Ireland in the same way as the product of the gravel washing process.

3.4 PHYSIO-CHEMICAL WASHING AND THERMAL TREATMENT IN EUROPE

Soilwashing in Belgium

Material suitable for soilwashing was shipped to a facility in Antwerp. The criteria for ensuring the soil was suitable for soil washing were both chemical and physical. The particle size distribution had to be such that no more than 15% of the particles were less than 63µm otherwise the process was not economically viable. The process was successful in extracting heavy metal, cyanide, sulphate and other inorganic contamination from the soil. It was also efficient at removing light hydrocarbons, but less so with viscous tars. In general the plant removed 85% of the PAH loading from sands and gravels. If the residual PAH loading in the washed gravel or sand exceeds generic Belgian soil guidelines the material cannot be recycled. If there was a risk that any individual PAH would exceed these guidelines after washing, the soil was sent for thermal treatment instead. PAH species were assessed individually, but in general if total PAH exceeded 1250 mg/kg the soil was thermally treated.

The soilwashing plant operated by DEC in Antwerp is the most sophisticated in Europe and combines many extraction techniques. Figure 3.4.1 below outlines the main elements of the soilwashing process applied to the gravels in Belgium. The process produces three main outputs: Clean gravel, clean sand and a filter cake/silt containing concentrated contamination. The two clean products are used in Belgian construction projects (e.g. roads) and the filter cake is dried and eventually removed to an engineered landfill. Typically 80% of the soil exported to Belgium for soilwashing was recycled for future use in construction.

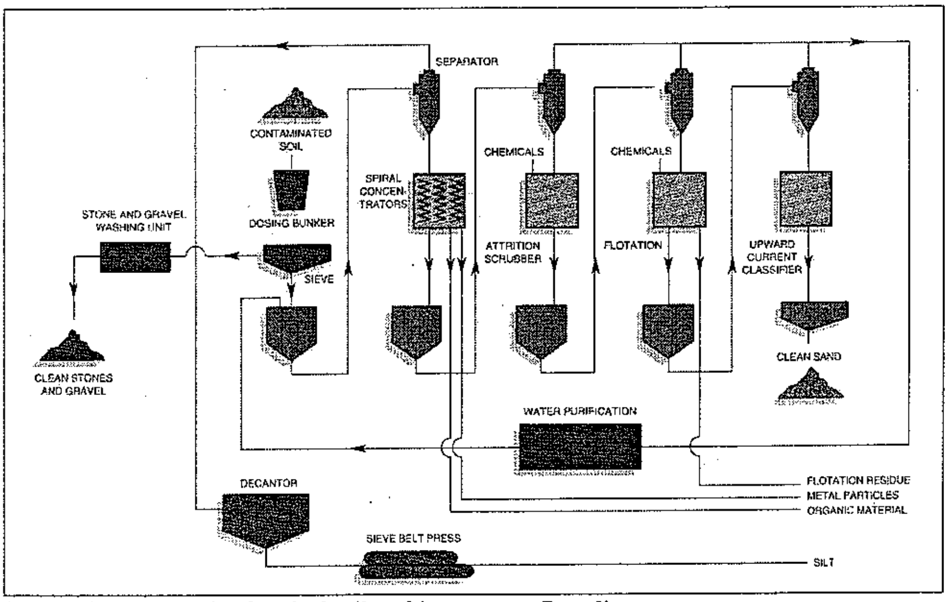


Figure 3.4.1 Physio-chemical soilwashing process flow diagram. Contaminated gravels with a sand content too high for recovery on site were exported to Belgium for treatment.

Thermal Desorption in Holland

Gravels that were too saturated with tar for soilwashing (Total PAH >1250 mg/kg) were shipped to Rotterdam for treatment. Thermal desorption operates at lower temperatures than incineration which has two advantages:

1. The process uses less energy and is therefore more economic.
2. The product is still marketable as a soil rather than the ash produced by high temperature incineration.
3. Emissions from the furnace are less noxious (and hence treated more economically) than those from incineration.

Once the soil arrived at the thermal desorption facility it was assessed based on soil chemistry and structure to establish whether the material would need improvement before entering the furnace. The gravels did not require improvement like the more cohesive alluvial silt and clay, which was mixed with granular material prior to treatment. This mixing was necessary to expose more soil particle surface area.

Thermal desorption of contaminants from the Dublin gravels took place at 800 to 900°C depending on the exact chemistry, moisture content and soil structure of the batch. The soil was discharged from the furnace and allowed to cool, whilst the air was drawn off into a series of filters and purification measures to remove dust, sulphur, organic contaminants and other fumes. Desorbing contamination from the soil is a relatively small part of the operation and most of the plant is devoted to purifying the air in order to meet Dutch air emission standards. The product is a black sand or gravel that still resembles a soil, but has no organic content and is therefore incapable of sustaining plant life. This soil is assessed against generic Dutch soil standards and recycled in civil construction works. The gravels are usually used in road construction, as there is a high demand for aggregates in the Netherlands.

4. CONCLUSIONS

By first isolating and subsequently removing the sources of contamination from the gravels further contamination has been prevented and on completion the site will be ready for development. The operation of the project under a waste licence ensured the involvement of the EPA and that the local environment was protected during the works. Recovery of gravels on site has provided cost savings for our client as less material had to be shipped to the continent for treatment. The Irish environment has also benefited from the use of recycled aggregate rather than quarried stone. Dry screening contaminated gravels was a faster way of recovering the gravels when compared with washing although a cleaner product was obtained with washing.

ACKNOWLEDGEMENTS

The author would like to thank Dublin Docklands Development Authority for their kind permission to publish this paper and Pierse-DEC Joint Venture for their contributions to this successful project.

REFERENCES

1. BG plc Property Division. *Guidance for Assessing and Managing Potential Contamination on Former Gasworks and Associated Sites (ver 2.3).* 1997
2. Brown, A.W. and Kingston, P.A. *The design and construction of a hybrid retaining wall at Sir John Rogerson's Quay, Dublin.* Proceedings of the International Symposium on Underground Construction 2001
3. Environmental Protection Agency. 1999. *Waste Licence 100-1*
4. Harris, M.R., Herbert, S.M. and Smith, M.A. 1995 *Remedial Treatment for Contaminated Land Volume IV: Classification and Selection of Remedial Methods.* CIRIA Publications
5. Houses of the Oireachtas. *Waste Management Act 1996.* Irish Statute Book at the Office of the Attorney General

12. Gravels and Planning: Rural Blessing and Urban Problem

David Ball, Consultant Hydrogeologist.

GRAVELS AND PLANNING: RURAL BLESSING AND URBAN PROBLEM

David M. Ball

Consultant Hydrogeologist

Emmet Bridge House, 38 Upper Clanbrassil St., Dublin 8

Abstract

Gravels and sands in a rural area are beneficial because they form shallow high specific yield aquifers and clean up recharge en route to deeper bedrock aquifers. Sand and gravel at depth in the bedrock is usually seen as a problem but with perseverance can be a significant benefit. By contrast gravel aquifers are a problem in urban areas. They become a problem because their presence, role and importance is either overlooked or poorly understood.

1. INTRODUCTION

Hydrogeology, development of groundwater supplies and planning in Ireland has tended to focus on bedrock aquifers. Gravels and sands have not received the same level of attention because they are perceived as a small scale and discontinuous resource. Gravels are often not explored or developed by drillers because they are disliked. Drillers discount gravels because drilling is still paid for on a price per foot of hole drilled, and gravel water resources are usually shallow. Gravels and sands also present problems for drillers because it is difficult to place a well screen in a water bearing gravel using the most common drilling method; down the hole hammer drilling. Water bearing unconsolidated deposits are prone to collapse, unless the borehole walls are supported by casing or drilling mud.

The focus to date on bedrock aquifers has influenced the discourse on aquifer protection and planning. This in turn has lead to simple guidelines for planners particularly regarding unsewered single houses and small developments. SR 6, and later derivatives, state that boreholes or wells should not be within 15 metres of a septic tank and percolation area, regardless of the method of borehole construction, depth of the water table or the nature of the aquifer and overburden. Whilst these guidelines are generally sound they are often applied rigidly by planning authorities, and several well researched and properly designed schemes have either been turned down or cast into uncertainty because the planners have not felt confident that they understood hydrogeology and that the guidelines permit interpretation and common sense.

Urban hydrogeology in Ireland is in its infancy. Most work by hydrogeologists in an urban setting is concerned with pollution and clean ups. Little attention has been paid to either the water resources of a town or city, the impact of building on these water resources, and in turn the impact of the groundwater flow system on the built fabric of the city.

2. GRAVELS: A RURAL BLESSING

Gravels and sands can be a refreshing and uplifting experience for hydrogeologists in Ireland. This is because they can be aquifers that conform to textbook principals. There is porosity, permeability and storage and a degree of homogeneity and predictability, that is not found in ancient, hard, fractured, bedrock aquifers.

Several papers in this seminar have already dealt with protection, exploitation and contamination in the context of gravel and sand aquifers. Below I will use three examples to illustrate how sands and gravels in different settings are generally a benefit in a rural setting.

Example 1 Doon Co. Limerick

Sand and gravel deposits can protect underlying groundwater resources in the bedrock from the inadvertent pollution taking place at the surface from either housing, urban development or farming.

A groundwater exploration programme in east Limerick for Limerick County Council was based on the GSI Groundwater Protection Maps for the county and also the GSI bedrock maps. Water availability and quality have been an issue in this area for some time. The County Council agreed to a programme of exploration to lead to the siting and development of a well field to provide a sustainable high quality supply for the village and a large area around.

The groundwater protection maps showed that the vulnerability of the bedrock aquifer was "high". The bedrock map showed that the bedrock below the village was Old Red Sandstone or Lower Limestone Shales. However the village is on the eastern margin of the Limerick Basin. To the south east of the village the above two aquifers were overlain by a featheredge of Ballysteen Limestone. This rock type can be productive where it is fractured, but generally it is a low permeability sequence of interbedded shales and muddy limestones. Given the objective and the apparent vulnerability of the aquifer it was decided to site exploration boreholes on the Ballysteen outcrop and drill through the Ballysteen to reach the underlying white, pink and pale green sandstones in the Lower Limestone Shales (Kiltorcan sandstones) below. The Ballysteen would be used as a protective cover. The design concept for future production boreholes would be to drill through the Ballysteen to the top of the Lower Limestone Shales, and then case and cement grout off the Ballysteen. After the 'pump chamber casing' had been cemented into place, the drilling would recommence to open up the producing section of the borehole in the Lower Limestone Shales. The one concern I had was the possibility of open vertical fractures in the Ballysteen protective cover. These fractures or faults could short-circuit the protection. The County Council naturally wanted any site to be close to roads and existing pipelines. Sites in these locations inevitably in rural Ireland are close to both stand alone unsewered rural housing and also farms with associated dungsteads, byres, slatted units and feeding troughs. I therefore selected a site and obtained permission for drilling in an area away from the village and in an area of good soil drainage above a spring line, hoping for a reasonable thickness of overburden to add to the protection afforded by the Ballysteen formation. I was particularly concerned about three houses with septic tanks upgradient of the site, the cattle in the pastures around and a large fault in the Ballysteen about 150 metres to the southeast. I found in the exploration borehole that the well-drained soils had arisen because the site was on a 24.5 metre thick deposit of dry and then saturated sands and gravels. Subsequent pump testing of the simple exploration borehole (without a cement grouted pump chamber casing) has not only proven the yield but also was excellent quality. Even the earliest water samples after just one day of pumping showed minimal TVC counts and zero Coliforms, Faecal Coliforms and Faecal Streptococci.

The deep sands and gravels could be developed as a source but even though the sands and gravels provide protection against faecal bacteria, there could still be a risk of elevated ammonia levels. Production boreholes aimed at the Lower Limestone Shales are planned for construction in November this year.

Example 2 Brittas Bay, Co Wicklow

A new development of holiday homes was planned for a large site at Brittas Bay in County Wicklow. The site was centred on the break of slope between the ancient shore line and the stabilised back dunes and hollows to the west of the main beach. The part of the site on the slope was underlain by a variable thickness of glacial clays overlying Ordovician slates. This bedrock can form a promising aquifer in terms of yield but I was concerned about very intensive cattle yards, and numerous unsewered caravan sites and new housing developments up hill and up gradient of the site. The lower part of the site was a proposed NHA and consisted of old beach deposits of sand and gravel overlying the bedrock. The clays appeared to have been eroded at the base of the old shoreline. I, the sanitation engineer and the architects decided to harness the beneficial characteristics of the sands and gravels to provide both a sustainable high quality water supply and dispose of highly treated effluent without effecting either groundwater levels or water quality for the NHA.

A well field of three shallow boreholes were drilled at the northern end of the site at the edge of the NHA. The effluent from the 50 or more houses would be treated by aerobic digestion feeding into a constructed wetland on the clays at the southern end of the site and then percolated back into the sands and gravels. Observation boreholes for determining the groundwater gradient and monitoring the effect of pumping were constructed in numerous positions across the site.

The three boreholes in the wellfield were able to provide a sustainable yield that was over double the peak-projected demand for the development, even though the boreholes were deliberately pumped at a gentle rate. The boreholes were only 25 feet deep. Each hole was constructed with a 5 metre long ribbed well screen with 2mm slots but covered by a 300μ mesh geotextile.

The boreholes in the well field were successful because they induced both shallow and deep groundwater flow to pass through the filter media of the fine gravel and sand deposits. This media was harnessed as if it were a slow sand filter at a water treatment works. Tests for quality at different times and seasons during a year showed that there were no faecal bacteria in the water supply. The pumping tests did not create a drawdown in the aquifer that in any way approached the percolation area for the wetland. There was therefore no risk of recycling the effluent back into the water supply.

Example 3 Sands and Gravels in Deep Karst Caves and Fracture zones Co. Laois

It is common to find karst features deep in Carboniferous limestones in the Midlands and west of Ireland. These features are found at depths of 30 to 90 metres. They are probably ancient karst features that were formed when sea levels were much lower than at present. These deep cavities and cave systems are now often below sea level and below the zone of active circulation of modern groundwater. They appear to be dormant groundwater flow conduits. They often have become clogged or filled with clays, sands and gravels washed down into them during or at the end of the last ice age.

The common perception of sand and gravel filled cavities deep in karst bedrock is generally negative. Drillers hate them because hole diameters at depth in bedrock boreholes are usually narrow and mean that neither casing nor screen can be usefully installed. It is common for there to be a problem of 'running' sands from the cavities when casing or screen cannot be used to control the sands and gravels. A stream of sand and fine gravel can flow into the borehole and if the pump is ill advisedly placed at the bottom of the hole or if the drawdown during pumping is too severe, these granular deposits can rise and flow into the pump. Pump life can be shortened to a matter of a few days or weeks. Therefore hydrogeologists and engineers do not generally perceive sands and gravels in cavities as a benefit. They are frustrated by the apparent availability of water that cannot be easily or cheaply abstracted.

Contrary to the common perception, sands and gravels in large conduits can be a great benefit. It is well recognised that Karst limestones in the West and some parts of the Midlands are extremely vulnerable to contamination. Soils are thin and provide little protection and large open conduits even at depth can provide rapid throughflow from a pollution source to an abstraction borehole. Therefore in these areas many domestic and group water scheme supplies are susceptible, periodically, to contamination. The history of this has, in part, lead to Ireland's recent reputation for poor quality rural supplies.

If we seriously attempt to utilise superficial or surface sands and gravel deposits to clean up and protect rural water supplies as in the two examples above, then why not use these same deposits for the same purpose at depth? Over many years I have seen several reports of groundwater exploration programmes that ended in negative answers when sands and gravels were encountered at depth. The reasons for 'failures' appear to be broadly; poor borehole design, lack of confidence by both drillers and hydrogeologists, lack of supervision and lack of perseverance.

The main problem with gravels and sands at depth are that the exposed area of sands and gravels is controlled by both the diameter or width of the karst cavity and the borehole. In other words little water can be drawn from a sand filled cavity which is only 1 metre wide. If a 6 inch diameter screen is placed against the sands and gravels in the cavity the open area is very small, even if the infill material has a porosity of 10% or more. Therefore the opportunity to obtain a reasonable yield by screening off the gravel only occurs where the cavity is very large, say 10 to 20 metres.

However, most karst caves or cavities are usually neither horizontal nor of uniform width. Therefore if a cavity only 1 metre wide is encountered by the borehole it does not necessarily mean that the cavity adjacent to the borehole is the same meagre width. It could be much larger. This possibility invites another method of exploiting the groundwater. Airlift development using the drill string with the down the hole hammer in the cavity usually leads to such violent disturbance that the discharge at the top of the hole appears to be a persistent torrent of water sand and gravel. However if the supervising hydrogeologist asks the driller to raise the drill string say 2-3 metres above the cavity and circulate air gently it is common to find that the sand and gravel content of the water diminishes with time. If the driller then lowers the drill string carefully cleaning and surging, down the hole in stages it has been found to be possible to maintain the yield with little or no sand flow. This is because the cavity around and adjacent to the borehole has been cleaned of gravel and sand and the turbulent flow has been kept to a minimum. With sensitivity and perseverance it is often possible to clean the gravel and sand from the cavity near the hole, but leave stable deposits in the rest of the cavity system. This has recently been achieved with gravel and sand filled cavities 1-2 metres wide at depths of 50 - 60 metres near Portarlington. The sustained flow was 5,000 gallons per hour.

It is obviously important to place a pump in such a hole well above the cavity, and to gently pump the borehole in gradually increasing steps. It is important to ensure that the pumping rate is not exceeded.

The overall message from a planning perspective is look carefully at sites and situations where sand and gravel are present but think vertically as well as horizontally, and insist on proper borehole design and construction to harness the beneficial characteristics of the gravel and sand.

3. GRAVELS: AN URBAN PROBLEM

Gravels and sands in an urban setting could be considered to have the same benefits for water supplies as found in rural settings. However there are few urban groundwater supplies and most towns and cities are fully serviced with sewers and storm drains.

Groundwater drainage through gravel and sand deposits is very important for our cities and towns, yet this importance is usually not recognised. The unrestricted movement of water through the sands and gravels is an important part of both the historical and modern substructure of our urban centres. The position of the water table and the availability of adequate supplies of groundwater were usually important considerations in the location and evolution of cities, towns and villages. Unfortunately the understanding of groundwater and drainage has been lost since the 19th century urban water supply and drainage schemes were constructed. Therefore planners, engineers, architects and even some hydrogeologists do not seem to fully recognise the extent, magnitude and importance of groundwater movement below urban areas. Nor do they fully recognise or address the potential repercussions of deliberately or inadvertently tampering with the groundwater flow system. This lack of awareness is understandable given that most developments are considered on a site specific basis. It is difficult with existing planning procedures and laws for developers and regulatory authorities to consider the local and wider implications of single developments, however large they may be. Part of the problem is that our cities and towns do not have an established infrastructure of monitoring boreholes.

I will use to recent examples from Dublin to illustrate the problem of groundwater, planning and sands and gravels.

Example 1 Archaeological Investigations in the Coombe, Dublin 2001

Earlier this year archaeologists found several old wells along the excavated alignment of the Coombe Relief Road. The engineers involved in the road project were worried about the high water levels in the wells and for some reason believed that these wells were "springs". They were concerned that flow from these 'springs' could wash away the hard core below the road and cause subsidence. They wanted to stick large diameter pipes on top of these wells and feed the 'spring discharge' via a syphon into a main carrier sewer. I became involved because advice was sought on the size of pipe necessary to take this imagined spring flow. I obviously corrected the misapprehensions regarding wells, springs and groundwater levels and also explained that connecting the sewer to the wells would probably lead to a reverse situation, where raw sewage and storm water become injected into the groundwater system below Dublin when the sewer 'surcharges' during a storm. Having dealt with the engineering aspects, I assisted the archaeologists in excavating a shallow stone lined well at the eastern end of the road. We had to dewater the well in order to reach the bottom. The hole contained a wooden pump stock (stick). There was a continuous and copious flow into the well from the gravels through the stone lining at a rate of 2,000 to 3,000 gallons per hour with a drawdown of about 4 metres. The static water level was at the old field soil level. There had been about 2 metres of fill above this level.

I realised during the efforts to maintain the dewatering that in the 18th century it would have been impossible to construct and line this well with such a flow rate. I also realised that the fields outside the city wall could not have been tilled if the water levels were so high. I inferred that the coarse permeable gravels were more fully saturated and water levels were higher than in the past. The most probable reasons for this are that either groundwater flow through the gravels had been impeded by, in effect, an underground dam, or that recharge (leaking water mains and sewers) had increased. The latter reason is less convincing, given that natural recharge is likely to have diminished during the last two hundred years, and the Corporation has recently made strenuous efforts to find and mend leaks. The underground dam has two obvious possibilities; the recent work to re-do the culverting of the Poddle River and the building of blocks of flats with basements along Patrick Street and the corner of Patrick street and the Coombe. It is difficult to be precise, but from observations of the soil section and the well it appears that the water table has risen 1-2 metres in this small area of Dublin. Fortunately there are few old buildings with basements in the Coombe.

Example 2 Spencer Docks Proposed Development Dublin 2000

The National Conference Centre and Spencer Docks proposed development is located on a curved wide strip of land to the east of the Royal Canal, which is underlain by man placed and naturally occurring sands, gravels and clays. The site is oriented at roughly right angles to the Liffey. The quay walls appear to be relatively impermeable. Groundwater flow in the area appears to be sub parallel to the alignment of the river. The proposed development consisted of massive blocks of offices and apartments. There was much discussion by planners, architects and developers of the 'permeability' of the overground built structures. There was much discussion of the ease of access of people, vehicles, wind, light and sun. However little consideration had been given to the permeability of the below ground structure. Because the developers wanted to keep heights down but maximise the use of the site the proposal for the full development involved the construction of a 3 storey deep, 22 acre underground car park. This 'dam' would have extended at right angles to the groundwater flow direction and extended some 6 - 8 metres below the water table. It would also have penetrated semi confined gravels below silt layers. The consequences of constructing an underground dam across the major sand and gravel aquifer on the north side of the Liffey had not been fully assessed. It was conceivable that water levels up gradient of the dam would have risen and that basements (bank vaults, church crypts, hotel kitchens and flats) and services such as sewers and cables in the 18th and 19th century east inner city would have been affected. These limited depth structures would not have been constructed with modern water tight concrete.

Spencer Docks is an easily identified large development project that would have probably altered the urban groundwater drainage in gravels, but over the last 4 years Dublin has seen numerous new smaller developments that have included major excavations and construction of deep underground car parks and service areas. Each one, individually, would not have probably created a dam, but together in clusters could certainly alter groundwater flow. Therefore the challenge for planners and regulatory authorities is to assess developments in context below ground as well as above ground. It could be said that assessing the over ground part is the easy part. It is easier to imagine or draw than the below ground part. Particular care should be taken with infill sites between existing large office and apartment developments.

Example 3 Dewatering for cleanups, construction and tunnelling

A final problem presented by sands and gravels in an urban area concerns dewatering. The previous paper refers to the dewatering to clean up the gas works site on Sir John Rogerson Quay. The concern about groundwater dams and or dewatering has been well described with this example. Other examples exist throughout the city of Dublin where developers have used secant or sheet piling to stabilise the sides of a large underground excavation and found large inflows through the floor of pit. The solution for the contractors has been to pump. This has lead to two consequences. First there has been a large, unregulated discharge of uncertain chemistry, probably brackish, water into the city's sewers and second an un-monitored lowering of the water table around the excavation. I understand that the owner of an 19th century pub is currently taking a developer/contractor to Court because his building (with shallow foundations) subsided and cracked during recent dewatering.

One of the intrinsic benefits of gravels and sands in a rural setting is their high permeability and potential as aquifers. In an urban setting the permeability of the gravels is seldom assessed. I have recently been called in as a last resort by contractors trying to drive a tunnel below a road and services in the Dublin docks. Though a report consisting of 13 volumes provided the raw data on the ground investigations and pumping tests in the area, little had been made of these data. For various reasons it has become essential to drive the pipe/tunnel at a depth of -7.5 m OD or about 4 metres below the water table through fine running sands underlain by very high permeability gravels. The tunnellers had been held up for 6 weeks trying different methods of stabilising the saturated sands.

Eventually the magnitude of the problem was realised and emergency dewatering boreholes were requested.

There is no difficulty constructing a borehole that can be pumped at a very high rate. A 12 inch borehole fully penetrating the sands and gravels can yield 70,000 gallons per hour with a drawdown of only 4 metres in the pumping well and 60 cms drawdown in an observation borehole 20 metres away. Therefore taking water out of the gravels is easy, but the difficulty occurs in trying to take water out of the shallow finer sands, and lower the water table in these sands. Taking water out of the gravels does not lead to dewatering of the sands because the horizontal permeability and specific yield is far greater than the vertical permeability. A solution that appears to be working was to construct shallow boreholes (14-15 metres deep), just penetrating the gravels and cobbles, and use a relatively coarse 1mm screen in the upper sands and a 3mm screen in the lower sands and top of the gravels. The holes are not being pumped using an electrical submersible but are instead are being airlift pumped. Airlift pumping can cope with running sands. The running sands diminished during borehole development and an extensive natural gravel pack has been created around the screen with time. The yield from the shallow boreholes is 5,000-15,000 gallons per hour. The water table has been lowered by 2-3 metres, though tunnelling work has to ease or stop for a time on either side of high tide.

4. CONCLUSION

The value of sands and gravels as aquifers for water supplies and as filters to protect the quality of groundwater resources needs to be more fully appreciated by planners, engineers, hydrogeologists and drillers. As I have said in this Seminar on previous years, the present method of specifying and pricing drilling does not lead to proper construction of sustainable water supply boreholes. The better use of the nations gravel deposits as either a source or a protection could lead to considerable savings in on - going water treatment costs in rural areas.

The presence of sands and gravels below cities and towns has been a historical benefit, but the insufficient awareness of groundwater flow below the urban centres now means that sands and gravels present numerous problems. It is important that planners and other professionals realise that unrestricted development below the water table in sands and gravels could lead to an unwitting degradation of the historical subsurface structure and foundations of cities and towns.