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on

THE ROLE OF GROUNDWATER IN SUSTAINABLE DEVELOPMENT

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FORWARD

The theme for the 15th annual groundwater seminar is the role of groundwater in sustainable development. A widely quoted definition of sustainable development is `development that meets the needs of the present without compromising the ability of future generations to meet their own needs'.

In the `Government for Renewal' programme published last December the new government committed itself to the preparation of a National Sustainable Development Strategy and proposed a Cabinet sub-committee to formulate and drive the strategy. In March of this year the creation of an Oireachtas Committee on Sustainable Development was announced. Hence the topic for the seminar this year is relevent in the prevailing political climate. I would hope that the material produced in the proceedings and the related discussion will provide the basis for an IAH contribution to the wider debate on sustainable development in Ireland.

This year marks the 150th anniversary of the establishment of the Geological Survey of Ireland. Over the last twenty five years the Geological Survey has made a significant contribution to Irish hydrogeology and to the IAH. It is therefore appropriate that the Director should address the seminar.

Over the past fifteen years the format of the seminar has been evolving. This year the committee decided to upgrade the proceedings as they are the principal source of hydrogeological material produced in Ireland.

Eugene Daly,
President, IAH (Irish Group)

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OUR GEOLOGICAL HERITAGE IS WORTH SUSTAINING

Peadar McArdle
Director
Geological Survey of Ireland

We in Ireland are fortunate in possessing a multi facetted geological heritage. The limestone pavements of the Burren, the granite hills of Wicklow and Donegal, the subtle landscape of drumlin and esker, the spectacular basaltic columns of the Giant's Causeway - these are all cherished aspects of our geological heritage. But they are not the only ones. This heritage is much wider and embraces the many ways in which we interact with our environment. This includes the provision of the whole range of earth materials required to sustain modern society - metals, construction materials, specialist non-metallic minerals and (most obvious in the context of this meeting) groundwater.

When the Geological Survey was established 150 years ago, society's needs of geologists were simpler: a better understanding of the country's geology and of its mineral resources. The impetus was the creation of jobs by landlords in mineral workings established on their estates. Indeed until comparatively recently this was still the key perception of a geologist's role - to support the discovery and extraction of mineral resources in a cost effective manner. It could be argued that this role has now created an enduring image that is no longer true but which the public is reluctant to discard. Geology is concerned not only with exploitation but also with conservation. We have no option in this matter - our total environment is now a resource. It is the new task of the geologist to provide choices for society in how it relates to this environment and to provide advice in relation to these choices.

An obvious starting point is with groundwater. Until comparatively recent times the geologist's function lay in advising on the most cost effective way of achieving a particular level of supply. This is still a valid and valuable preoccupation, and one of pride for many of today's attending geologists. However there are now additional concerns relating to the protection of groundwater quality which equally require the geologist's attention. Given that many of our aquifers tend to be unconfined and shallow, they must be considered generally vulnerable to pollution. Water moves freely along fractures in limestone or between grains in gravel, but this permeability - so valued for abstracting the groundwater - can be a problem if pollution is introduced. Accordingly considerable effort is being devoted to groundwater protection schemes and, in particular to defining source protection zones around abstraction points. I am aware that such studies are now relatively sophisticated and involve integrating many different data sets. I think you will recognise this balanced approach as a practical example of the implementation of the principle of sustainable development, the subject of this conference.

In the offshore environment a parallel evolution of geological needs is also evident. In earlier decades there was a demand for high quality geological data to support hydrocarbon and mineral exploration. Potential minerals include seaward extensions of base metal deposits found on land, coal deposits, sands of distinctive composition, and gravel. It is likely that this interest will persist into the next century. However it will be accompanied - and tempered - by rising concerns about maintaining the marine environment itself. The maintenance of fish stocks as well as the development of wind and fish farms are additional facets where geological science can help. In addition it can assist in coastal zone management through studies of sediment movement and the definition of areas vulnerable to coastal erosion.

In the minerals sector, Ireland in recent decades has been a significant producer of basemetals, industrial minerals (gypsum, barite) and construction materials. In addition there is potential for the discovery of a range of additional metallic and non-metallic resources. The role of the geologist in all this activity is quite clear and has not substantially changed in recent decades. Change has come recently in the form of additional tasks which now require attention and these all relate to environmental aspects of mining. Geologists are now giving increased attention in the pre-production stage to groundwater resources which may be affected by mining, as evidenced in the recent case of Galmoy. When mining has ceased, as at Avoca, increasing investment and research is being directed at land remediation. These are themes which once more are in harmony with the principles of sustainable development.

Can we pursue sustainable development while at the same time encouraging the extraction of non-renewable mineral resources? I believe that we can, although it clearly presents us with a challenge. As minerals became scarcer their unit value increases and so deposits which are uneconomic today may become viable in the future. More isolated deposits, or deposits occurring at greater depths may become economically attractive. The same may apply to lower grade deposits or those with relatively difficult metallurgical properties. At the same time research in the utilisation of metals (and other mineral products) can be expected to lead to much lower unit consumptions, which will slow down the rate of depletion of mineral resources. This may not be an idea solution, but with prudent, well-informed planning we can approach very close to sustainability.

Reconciling the often-conflicting needs of the present and future generations lies at the heart of sustainable development. Resolving such choices presents challenges to the geologist which cannot be ignored. There is nothing esoteric in such challenges. As a simple example, let us consider the conflicting challenges of the limestone bedrock of the midlands of Ireland. The limestone itself provides special landscapes in areas such as Ben Bulben, Cashel and the Burren. Limestone pavements evoke strong images of the origin of these rocks as carbonate muds and sands on a tropical sea platform during the carboniferous. However for many people these limestones represent the host rocks for many attractive basemetal deposits, such as the zinc deposits of Navan, Galmoy and Lisheen. While they have always been a source of high employment, to many people it is only in recent times that they have become centres of excellent environmental practice. Quarries in these same limestones provide the raw materials for cement, aggregates and agricultural lime. The limestones are frequently fractured and cavernous and therefore are important aquifers in many parts of the country. Where cavernous (or karstic), the drainage may be by means of underground conduits and, if these become overloaded or blocked, then surrounding countryside will be subject to flooding during periods of sustained heavy rainfall. However if drainage were efficiently organised yet another conflict would emerge: the wetlands around turloughs would deteriorate and lead to the destruction of special habitats for a wide range of specialised fauna and flora. These various concerns are not necessarily always in direct conflict with each other, but it is essential that society forms a balanced view of its needs, based on all the information available.

The Geological Survey is building up a series of databases and map series which we believe are highly relevant to the needs of society in planning environmental and resource utilisation. These can be summarised in the context of the five programmes which we operate:

Bedrock Programme: We are currently compiling a set of 1:100,000 scale bedrock maps for the whole country which is expected to be fully published in 1997. These maps will be the first comprehensive set published for more than a century. They are of great interest to the broad spectrum of our customers and they will be accompanied by guidebooks which are aimed at the general public.

Subsequently the publication of 1:25,000 scale maps will be resumed in order to provide site-specific information.

Quaternary Programme: This programme is concerned with unconsolidated materials overlying bedrock, such as clays, sands, gravels and glacial tills. Maps are published on a scale of 1:25,000 and include depth-to-bedrock information. A geotechnical database is maintained for urban areas and provides detailed information for engineers on matters such as depth-to-bedrock.

Groundwater Programme: The programme is largely concerned with maintaining, improving and computerising well records and hydrogeological data, as well as producing thematic maps – aquifer, groundwater vulnerability and groundwater protection. These outputs are being achieved at present by means of joint projects with local authorities and third level colleges. The programme is also concerned with providing advice within the Department of Transport, Energy and Communications on the groundwater aspects of the proposals to mine Zinc/Lead at Galmoy and Lisheen. A project on karst limestones has commenced, jointly with TCD, and this links with work carried out on flooding in karst areas and with the databases.

Minerals Programme: This programme maintains three separate databases. The largest, the Exploration Open File Database, contains the records of all commercial exploration performed in Ireland over the last forty years, including geochemical and geophysical surveys, geological mapping and drilling. The Mineral Localities Database comprises historical information on all mineralised localities recognised in the last 200 years. The final of the three databases, Mine Records Database, has mine plans relating to mines operated in Ireland over the last 200 years.

Marine Programme: Information on coastal and offshore geology is maintained in the marine database and recorded on maps at a scale of 1:250,000. The information relates to the mineral resources, engineering projects and environment of our extensive sub-sea region.

A major challenge for the Geological Survey in the future is to integrate the output of all these programmes. We are conscious that the value of our organisation lies not just in the information itself that we hold but in the added-value that we bring to it for the benefit of our customers. To this end we are committed to developing a GIS-environment in which all databases will be harmonised and connected. A digitised map production system with GIS capability has already been brought into operation, but its function at present is confined to expediting the publication of the bedrock maps. However we intend to tap into its full potential as soon as possible and this will involve GIS-type operations. I believe that this could make a significant contribution to the quality of sustainable planning in Ireland because its powerful integration of data will assist in discriminating between development choices.

Geological Surveys are in a key position to contribute to the protection and sustainable development of the environment. Of course they are not alone in this - their contribution can be readily integrated with those of other disciplines (ecology, climatology etc). Geology has an essential role in identifying environmental problems, understanding causes and developing solutions. Among the challenges facing geologists is that of communicating effectively with the public and decision-makers. The relevance and worth of geology to Ireland is still imperfectly understood and, with this in mind, the Geological Survey is producing a set of TV programmes this year on the subject. This will be one of a number of events organised during 1995 to mark our 150th anniversary. We have changed considerably since 1845 and are pleased to find that we hold the skills essential to assist in a range of issues relevant to sustainable development.

INTEGRATING ENVIRONMENT AND DEVELOPMENT - THE USE OF PRICING AND OTHER INCENTIVES TO ACHIEVE EFFICIENT USE OF ENVIRONMENTAL ASSETS - 10 COMMANDMENTS

Frank J. Convery,
Environmental Institute,
University College, Dublin.

ABSTRACT

The use of market instruments and resource charges are essential elements of modern resource and environmental management. Compared to the use of non price rationing or the use of command and control strategies, market instruments will deliver a better environment at less cost. Certain conditions must be met if such instruments are to be effective; notably, property rights must be assigned. In Ireland, market based instruments are used less than in most OECD countries. Unless this changes, the prospects for sustained management of our environmental and natural resource assets are poor. This applies also to groundwater.

Background

Every profession has its idee fixe, its core value, around which the solutions it proposes to every challenge circle. Take a flooding problem: the engineer will propose a structural solution - deepen the river, build up the bank, build the dam; the lawyer will propose a set of regulations governing the use of the water and the land, and legislation governing the compensation of those adversely affected; the planner will propose a zoning solution - zone for wetland uses the land that can be expected to flood frequently; the ecologist will propose (after first calling for more study) that nothing should be done - let nature take her course; the forester will propose that trees be planted, to take advantage of their high interception and evapo-transpiration rate; the sociologist will examine how different socio economic and ethnic groups are affected, and how empowerment is distributed. The economist argues that none, some of all of the above may be relevant to the solution; it depends on the costs and benefits of the alternatives. He or she will also look to markets as solutions - how to create a market in flood reduction, where the beneficiaries, e.g. those downstream, could transact with those upstream to reduce the incidence of flooding.

In this presentation, I wish to dwell briefly on the use of market based incentives as means of achieving efficiency in the use of resources. The following points can be made:

1. For markets to work effectively, three prerequisites must be met:

* First, resources must be owned, in the sense that some individual, community, company or other organisation must be *willing and able* to exclude others from access thereto. This has nothing to do with legal ownership; the latter can prevail, and the "owners" cannot limit access (e.g. the absentee owner of fishing rights in Ireland); conversely, ownership may not exist in a legal sense, but an individual or set of individuals are able and willing to limit access (local anglers on the Western lakes post license imposition some years ago).

* Secondly, transactions must be facilitated. The owners must be willing and able to transfer the rights, and to accept payment therefor.

* Thirdly, consumers and producers must be adequately informed as to the implications of their consumption and production decisions.

2. When these conditions are met, natural and environmental assets will be traded at a price which reflects their scarcity value.

If the resources are very plentiful relative the demand, the price will be low (perhaps zero). If supplies are scarce relative to demand, price will be high.

3. When these conditions are met, the net benefit - difference between benefits and costs - will be maximised.

But this net benefit will vary depending on how income is distributed; if the distribution of property rights is changed, then the distribution (and possibly the size) of net benefits will likewise change.

4. There is a distinction between net financial benefit - which accrues in the form of cash - and economic benefit - which includes a consideration of market and non market mediated costs and benefits.

The benefits which an activity yields which are not captured by the provider are called external benefits; the costs which activity imposes which are not borne by the perpetrator are called external costs. Economic analysis attempts to incorporate a consideration of external costs and benefits in the estimation of net economic benefits.

5. It is precisely the fact that environmental and many natural resources are not owned, and producers and consumers are not adequately informed as to the implications of their actions, that results in environmental degradation and resource waste.

Examples abound; upland farmers cut down the forest, and don't bear the costs of the resulting flooding downstream; households burn coal in open fireplaces, without bearing the costs of the resulting pollution; by extirpating species from the planet, one generation eliminates the genetic potential forever which might be availed of by future generations; farmers overgraze the commonage because none of them individually has an incentive to conserve it.

6. Unless property rights are assigned, and market type incentives introduced, then a society will waste its natural resource and environmental endowments.

Ireland ranks as the bottom of the OECD league when it comes to using market based incentives (OECD, 1994). Unless we can change this, the outlook for our natural resource and environmental endowments is poor.

7. For most situations, the use of emission and resource charges is a much more efficient way to manage our environmental assets than the traditional "command and control" approaches.
The use of charges maximises the choices available (recycling, change of inputs and outputs, recycling and re-use) encourages innovation, generates revenue, encourages conservation of assets by producers and consumers, and provides feedback on performance (Hahn, 1989). command and control usually encourages a focus on expensive and relatively inefficient end-of-pipe solutions.

8. If is not clear why we as a society have such an antipathy to the use of market based incentives, but the following can be hypothesised:

* Relatively high income tax rates, which are an involuntary "seizure of assets" by government, generates an antipathy to any other form of "taking". The "double taxation" arguments against the use of water charges are entirely spurious - why not apply the same logic to charges for TV licences, car registration, property tax on companies, excise duty on whiskey and petrol, VAT on electricity bills etc.? But it is not surprising that people losing almost 50 per cent of their income at the margin will attempt to create another Boston tea party out of local charges.

* The lack of linkage between tax raising and spending.

The UK and Irish traditions is not to "earmark" money raised, so there is no potential for "buying off" opposition by agreeing to spend the funds raised for purposes which command political support.

* Rural ethos, which tends to view life as a zero sum game, while the essence of market transactions is the notion of mutual gain.

9. Groundwater seems to share all of the characteristics which would ensure that the asset is simultaneously wasted and environmentally damaged.

The decision by the court in the Galmoy Co. Kilkenny groundwater case seems to imply that the property rights to the water do not reside with those sharing the aquifer who would use the water, i.e. that there is no "taking" *per se,* in cases where the water table is lowered, and no payment for the use of same must be proffered. This may overstate the case, since it seems that there are provisions of the planning permission which provide for replacement of water loss by the developer. But what would the situation be if planning permission were not required? As pressure on water resources, especially in the East, intensifies, there should be absolute clarity as to the assignment of property rights; otherwise, resources will be wasted, and lawyers mediating the tangle will be the main beneficiaries.

The absence of a price per unit for water drawn from an aquifer ensures that it will not be used efficiently. We all squander that which is free. "Free" water may be appropriate in parts of the West, where supply so far exceeds demand that there never will be a shortage; in the East, this happy situation is unlikely to be universal.

10. But in adjusting for "market failure" by some combination of property right assignment and charges (internalising costs), it is important not to forget that power goes with property rights.

The manner in which rights are assigned must be equitable and be seen to be so.

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THE PRINCIPAL CHARACTERISTICS OF THE FLOW REGIME IN IRISH AQUIFERS.

Eugene P. Daly - Eugene Daly Associates

ABSTRACT

This paper briefly describes the groundwater flow regime in Ireland. It discusses the influence of the particular characteristics of this regime on the development, contamination and protection of the main aquifers.

INTRODUCTION

Groundwater is an integral part of the hydrologic cycle and therefore of the physical environment. In the geosphere, groundwater is the transport medium for the movement of contaminants.

Before considering the sustainable development of groundwater in Ireland it is necessary to have a basic appreciation of the hydrogeology of the main aquifers and the overall groundwater flow regime.

This paper briefly describes the principal characteristics of the flow regime in Irish aquifers as we understand them today. It also discusses the influence of these particular characteristics on the development, contamination and protection of groundwater.

CHARACTERISTICS OF THE FLOW REGIME

When working in the hydrogeological environment in Ireland three factors should always be kept in mind. They are:

1) The geology is complicated,

2) The climate is wet and unpredictable, and

3) The Quaternary deposits (subsoils) which cover much of the lowlying ground have an important impact on the flow regime in the underlying rocks.

These are obvious statements. Nevertheless they are ignored at one's peril.

The groundwater regime in Ireland is no different to that elsewhere on the globe. However, there are particular nuances of the flow system here that are somewhat different from that in nearby countries. The flow regime can be conveniently characterised under seven headings which are outlined below.

GEOLOGY

Aside from the younger strata in the northeast the rocks in Ireland are old, indurated and with a complex history. Almost the full geological succession exists on the island and it has been folded and faulted into a very tight space.

Owing to the widespread distribution of Quaternary deposits and almost continuous faulting, the full geological picture is rarely known in sufficient detail at the scale of most groundwater investigations, unless drilling logs or geophysical well logs are available.

As a consequence of the geology the aquifer units are relatively small and frequently have complex boundaries. Faults which 'as rule of thumb' can be considered to occur every 0.5 to 1km have a considerable impact on the flow regime in these aquifers.

A compilation exercise carried out by the Geological Survey (Wright, et al, 1982) showed that major aquifers cover about a quarter of the Republic with estimated surplus resources equivalent to about 50mm/y. The different types of limestone aquifer and the sands and gravels account for the largest part of the groundwater throughput.

RECHARGE

Rainfall is plentiful (800-1400mm/y) over the main aquifers and is well distributed throughout the year. Actual evapotranspiration ranges from 400-500m/y. Therefore potential recharge (or moisture excess) over these areas will range from 400-1,000mm/y. There is a general increase from east to west and also with elevation (Figure 1).

East of a line say from Belfast to Cork there is a definite recharge period of 4/5 months from mid-October to mid-March and general recession (3-7 months, in the southeast) thereafter. West of this line the average situation is less well defined. There is heavier recharge, 20% to 50% more rainfall per month, with a much shorter non-recharge period (1-4 months, in the northwest). Here soil moisture deficits' are much less and last for shorter periods.

Recharge of the main aquifers occurs via a number of different mechanisms, ie. direct infiltration through the soil and overlying Quaternary deposits and indirectly through swallow holes (limestones), influent (losing) streams and shallow groundwater flow off non-aquifer areas.

In many areas the storage volume depleted during the groundwater recession period is significantly less than effective rainfall (available recharge). In these circumstances the recharge is "rejected". Most well hydrographs show that the storage depleted during the previous recession is replenished by late December/early January each year. Thereafter much of the available recharge is rejected (can be up to 50% of the total). Evidence of it can be seen on the ground over the winter months in the flow of high level ephemeral springs and seeps, flooding and the very large discharge rates of the major springs and stretches of certain streams. The winter of 1994/'95 is a perfect example.

The ample recharge replenishes the resource each year. It balances the relatively low storage in most Irish aquifers and results in relatively small cones of drawdown which are more practical to protect.

Although the annual rainfall tends not to vary by more than 25% from the annual average at any particular station, any individual month can have a variation from almost no rain to 2/2.5 times the normal monthly rainfall (eg. 2/3 months in the winter of 1994/'95). In these

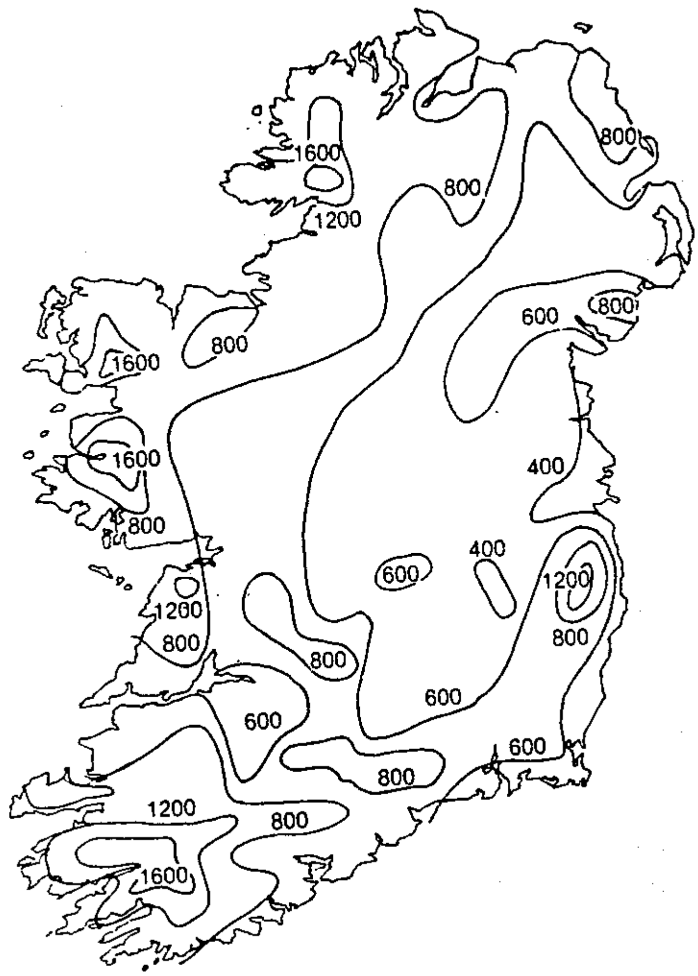

Figure 1. Potential recharge (moisture excess) after Collins, et. al.,1986.

circumstances effluents can overwhelm disposal/treatment systems that are designed on average figures.

In these situations it is frequently necessary to cover wastes to maintain effluent volumes at average levels and be very precise in the timing of land disposal of waste. This is particularly true in the west and also for elevated areas.

The large volumes of recharge do provide significant dilution of effluents in the ground once the initial flush of effluent has been washed through the system where that is hydraulically possible. It also provides an incentive to eliminate sources of pollution with the prospect of having better quality water at the end of the recharge period.

PERMEABILITY

Fissure flow predominates in the bedrock aquifers (aside from the younger rocks in the northeast) owing to their age and complex history.

The development of permeability in these strata has resulted from a number of geological processes, such as dolomitisation, karstification and structural deformation. Most aquifers in this country exhibit several of these processes to some degree. In some instances the strata have been affected by different processes at different times in their geological history. For example, the permeability of the dolomites of the South Midlands has been produced by early faulting/dolomitisation and enhanced by subsequent weathering (Daly, 1993a).

On a local scale the impact of these processes on the geosphere is quite irregular as is the permeability they create. Furthermore some geological strata are more susceptible to the development of permeability by individual processes than others, eg., most sandstones to structural deformation and some limestones to karstification. The resulting permeability in Irish aquifers is very variable and hence difficult to predict especially in the case of the limestones.

Permeability is generally greatest, by an order of magnitude, in the top 30m/40m of bedrock. It is here that the processes that create the permeability (aside from dolomitisation) are most active.

A conceptual model (Daly, 1993b) has been developed for Irish aquifers in which all of the bedrock aquifers have been grouped into a number of zones where the individual aquifers have similar characteristics (Figure 2). In any one of these zones the dominant source of the permeability in an individual aquifer is the same. In the case of the Waulsortian "reef" a massive pure limestone and major aquifer, faulting and subsequent karstification are the dominant sources of permeability in the Southern Synclines whereas in the South Central Region it is faulting/dolomitisation and weathering. In the north the intensity of faulting is diminished, the rocks are not dolomitised and there is little deep or widespread karstification. In these areas the "reef" is not considered to be a major aquifer.

Owing to the secondary nature of the permeability in these aquifers the storage is relatively low. However, as has been mentioned above it is balanced by the high recharge that occurs over a relatively long period each year. As will be described below additional storage is frequently available in the Quaternary deposits that overlie many parts of the major aquifers.

Owing to the unpredictable nature of the permeability it can frequently be quite difficult to locate high transmissivity zones in which to site high yielding boreholes. Low storage and high permeability generate large cones of depression in aquifers. In Ireland this is generally not so due to the high recharge and additional storage in the Quaternary deposits. In the east of the country in the years with a long non-recharge period streamflow can be seriously affected in upland non-aquifer areas where the Quaternary deposits are thin or absent.

The absence of primary porosity and rapid water movement in many of the bedrock aquifers provides little opportunity for attenuation of contaminants. The karst situation is the extreme example of this. Here the flow direction is very unpredictable and may even vary with the time of year (high/low flow). In this situation it can be very difficult to predict the movement of contaminants and hence to monitor a potential source of groundwater contamination.

In certain of the major bedrock aquifers groundwater protection can be extremely important if there is no natural protection provided by the Quaternary deposits.

HYDRAULICS

Owing to the compact nature of the geology, the hydraulic conditions can be quite variable over relatively short distances although unconfined conditions are dominant in the main rock

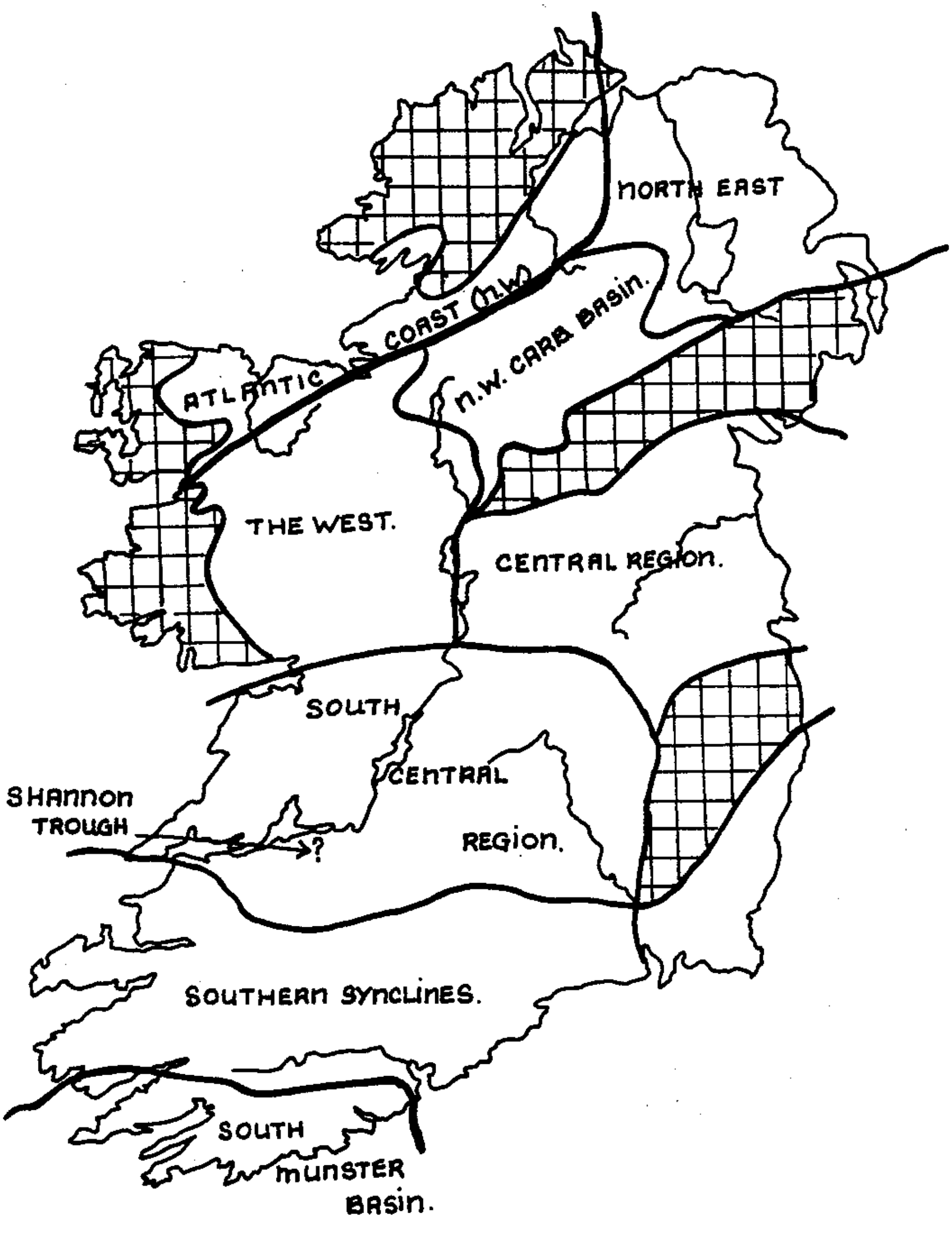

Figure 2. Conceptual model of Irish aquifers.

aquifers. Much of this variation is a result of the influence of the Quaternary deposits. The bulk of the groundwater movement occurs in the outcrop/subcrop areas, at shallow depths, relatively rapidly along short flow paths (Daly, 1989) and discharges into springs or the normally effluent streams which cross the aquifers. There are influent (losing) sections of streams especially in the sand and gravel and karst limestone aquifers.

An estimate of the groundwater component of riverflow in the River Nore from 1972-1981 gave an average value of 50% of total flow or 26% of rainfall (Daly, in press). A conceptual model of the hydraulic regime in the Midlands (Daly,1993b) suggests that the bulk of the throughput (75-80%) of Irish (bedrock) aquifers flows through the top 20-30m below the summer water table level (Figure 3). A number of modelling studies carried out over the past few years support this view. It is probable that the bulk of the rejected recharge, spoken

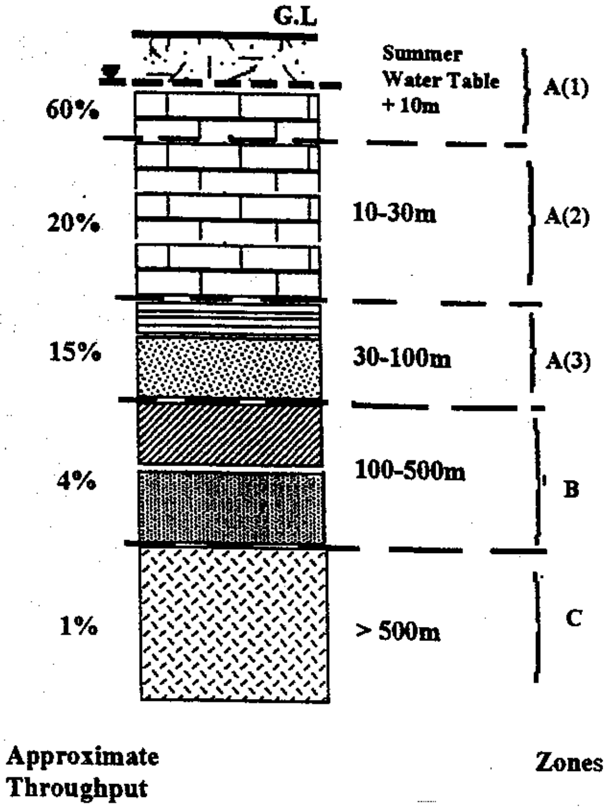

Figure 3. Conceptual model of the groundwater flow regime in the Midlands

of earlier, moves in the 10m below the normal winter water level. There is thought to be very little flow at depth (ie., in excess of 100m). What flow there is is likely to be along faults (Barrow, et. al., 1991) and with a significantly different chemistry to that close to the surface.

The cones of drawdown from most large wells although generally small are likely to encounter flow barriers or recharging boundaries (streams/faults, etc.) within a short distance with the inevitable consequences for yield and/or water quality.

Contaminants moving underground will concentrate in the upper layers and are likely to move quite quickly to nearby surface discharge points except in the karstified limestones.

Aquifer and source protection zones will generally be small as a consequence of the ample recharge and complex as a result of the hydraulic regime described above.

WATER TABLE

In the bedrock aquifers the water table is generally a subdued reflection of the topography, less than 10m from the surface with an annual fluctuation of less than 5m. Notable exceptions are found in a few areas. For example in some of the karst limestone areas the water table is over 100m deep with an annual fluctuation of around 30m.

Perched water tables are common in the winter particularly in the Quaternary deposits. In certain small areas detailed summer water level surveys do show subtle variations in the water table in response to different hydrogeological conditions. The water table gradient generally ranges from 0.001 to 0.05 in the principal unconfined aquifers and from 0.01 to 0.1 in the aquitards.

The shallow water levels have permitted development of groundwater by shallow dug wells, infiltration galleries, etc.

In permeable, near surface situations shallow water tables do allow relatively rapid access of contaminants to the water table with little opportunity for attenuation.

Areas of shallow water tables generally do require a high degree of protection.

QUATERNARY DEPOSITS

These deposits play an extremely important role in the overall hydrogeological regime in this country. The bedrock aquifers are generally overlain by a thin layer (< 10m) of Quaternary (unconsolidated) deposits whose lithology, thickness and permeability are very variable. These deposits have a major effect on the hydrogeology of the underlying rock aquifers and aquitards. They influence the hydraulic conditions and the amount of recharge, are pathways for discharge and provide additional storage for the underlying strata. For example numerous springs fed by the limestones discharge via lenses of sand and gravel. These thin deposits are also a very important source of baseflow to the river network throughout the country.

Where the Quaternary deposits are sufficiently thick (> 10m), permeable, saturated and extensive they are considered to be an aquifer in their own right. There storage (5%-15%) is higher than in the bedrock aquifers and the water table is frequently less than 5m below the surface with an annual fluctuation of less than 1.5m.

Where the Quaternary deposits are of sufficiently low permeability and/or thickness the movement of contaminants from the surface may be restricted or prevented and/or the concentration sharply reduced by physical, chemical and biological processes active in these strata (Daly, 1985a).

Quaternary aquifers are usually difficult to delineate but can be very productive and inexpensive to develop.

The vulnerability of the unconfined parts of the major aquifers to contamination is largely determined by the extent and permeability of the overlying Quaternary deposits.

WATER CHEMISTRY AND QUALITY

A major review of groundwater quality (Wright, et. al., 1983) concluded that groundwater pollution is not yet a widespread problem in Ireland. The results of sampling the principal large springs (almost 200, mainly from the unconfined parts of the limestone and sand and gravel aquifers) in the Republic in 1985/'86 showed that the waters are generally hard (Total Hardness of 200-400 mg/l as $CaCo_3$) with low mineralisation (200-500 mg/l) (Daly, Geraghty and Aldwell, 1989). The report also concluded that groundwater quality was good but with some exceptions.

Numerous studies of groundwater quality have also shown that many low yielding wells used for farm and/or domestic supplies are contaminated by the effluent from nearby point sources of pollution. In these situations the effluent is generated close to the low yielding wells and its impact is limited to quite a small area and confined mainly to the upper parts of the geological environment (Daly and Woods in press).

CONCLUSION

In Ireland groundwater is a considerable natural resource, is largely uncontaminated as a consequence of the characteristics of the hydrogeological regime but is in need of protection for use by the current and future generations.

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GROUNDWATER PROTECTION

IN IRELAND : A SCHEME FOR THE FUTURE

Donal Daly
Groundwater Section
Geological Survey of Ireland

ABSTRACT

The protection of groundwater in Ireland is an important national objective, which can be achieved by using groundwater protection schemes as part of the planning process. This paper proposes a scheme which (i) takes account of the hydrogeological situation in Ireland, (ii) is based on sufficient hydrogeological information to be defensible and (iii) is achieveable. The scheme, which consists of groundwater protection maps and a code of practice for potentially polluting activities, provides a framework for decision-making and a logical structure for the protection of groundwater. The use of the scheme by local authorities will help ensure that new developments in Ireland are sustainable.

INTRODUCTION

The protection of groundwater quality from the impact of human activities is a high priority for land-use planners and water resources managers. This situation has arisen because:

- groundwater is an important source of water supply;
- groundwater moves slowly through the ground and so the impact of human activities lasts for a relatively long time;
- groundwater may be difficult to clean up, even when the source of contamination is removed;
- unlike surface water where flow is in defined channels, groundwater is present everywhere;
- human activities are posing increasing risks to groundwater quality;
- EU policies and national regulations are requiring that pollution must be prevented as part of sustainable groundwater quality management.

Since the mid 1980s, a number of local authorities - Offaly, Wexford, north Cork, Galway and Louth - have been successfully using groundwater protection schemes. These are based on a relatively basic and simple scheme proposed by the Geological Survey of Ireland (Daly, 1986; Daly, 1991) and are appropriate to the available hydrogeological information and planning needs of that time. Now a more comprehensive scheme, using a greater geological and hydrogeological input, is proposed to enable better and more defensible decision-making in land-use planning and environmental protection. The GSI has drawn up and is currently using a comprehensive scheme, which is based on hydrogeological concepts and a practical and pragmatic level of data collection and analysis (Daly (1995). This paper provides a summary of the scheme.

GROUNDWATER PROTECTION THROUGH LAND-USE PLANNING : A MEANS OF PREVENTING CONTAMINATION

There are a number of ways of preventing contamination, such as improved well siting, design and construction and better design and management of potential contamination sources. However, one of the most effective ways is utilising groundwater protection schemes as part of the planning process.

Land-use planning, using either planning, environmental impact assessment or water pollution legislation, is the main method used in Ireland for balancing the need to protect the environment with the need for development. However, land-use planning is a dynamic process with social, economic and environmental interests and impacts influencing to varying degrees the use of land and water. In a rural area, farming, housing, industry, tourism, conservation, waste disposal, water supply, etc., are potentially interactive and conflicting and may compete for priority. How does groundwater and groundwater contamination prevention fit into this complex and difficult situation, particularly as it is a resource that is underground and for many people is "out of sight, out of mind"? Groundwater protection schemes are an essential means of enabling planning authorities to take account of both geological and hydrogeological factors in locating potentially polluting developments; consequently they are now an essential means of preventing groundwater contamination and pollution.

ENVIRONMENTAL PRINCIPLES

As a means of protecting the environment, the following principles are now generally recommended and are part of Irish environmental policy:

- the principle of sustainable development, which is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987);
- the precautionary principle;
- the principle that environmental protection should be an integral part of the development process;
- the "polluter pays" principle, which requires that the environmental cost should be incorporated in any development proposals.

These principles provide the basic philosophy for the groundwater protection scheme outlined in the following sections. Also, the concept of risk and the requirement to take account of the risk of contamination to groundwater from potentially polluting activities have been integrated into the groundwater protection scheme.

RISK AND RISK MANAGEMENT - A FRAMEWORK FOR GROUNDWATER PROTECTION SCHEMES

Groundwater protection schemes are usually based on the concepts of groundwater contamination risk and risk management. In the past, these concepts were background, often implicit, sometimes intuitive factors. However, with the language and thought-processes associated with risk and risk assessment becoming more common, relating a groundwater protection scheme to these concepts is likely to be beneficial in that it encourages a rigorous approach and is appealing to decision-makers.

The **risk** of contamination of groundwater depends on three elements:

i) the **hazard** provided by a potentially polluting activity;
ii) the **vulnerability** of groundwater to contamination; and
iii) the potential **consequences** of a contamination event.

Risk management is based on analysis of these elements followed by a **response** to the risk. This response includes the assessment and selection of solutions and the **implementation of measures** to prevent or minimise the consequences and probability of a pollution event.

The **hazard** depends on the potential **contaminant loading**. The natural **vulnerability** of the groundwater dictates the **likelihood of contamination**. The **consequences**, if a contamination event occurs, depends on the **value** of the groundwater, which is normally indicated by the aquifer category (regionally important, locally important or poor) and the proximity to an important groundwater abstraction source (a public supply well, for instance). **Preventative measures** may include, for instance: control of land-use practices and in particular directing developments towards lower risk areas; suitable building codes that take account of the vulnerability and value of the groundwater; lining of landfill sites; installation of monitoring networks; specific operational practices. Consequently, assessing the risk of contamination to groundwater is complex. It encompasses geological and hydrogeological factors and factors that relate to the potentially polluting activity. The geological and hydrogeological factors are (a) the vulnerability to contamination and (b) the relative importance or value of the groundwater resource. The factors that relate to the potentially polluting activity are (a) the contaminant loading and (b) the preventative measures.

A groundwater protection scheme should integrate these factors and in the process serve to focus attention on the higher risk areas and activities, and provide a logical structure within which contamination control measures can be selected.

OBJECTIVES OF THE GROUNDWATER PROTECTION SCHEME

The overall aim of the groundwater protection scheme is to preserve the quality of groundwater, particularly for drinking purposes, for the benefit of present and future generations.

The objectives, which are interrelated, are as follows:

- to assist the statutory authorities to meet their responsibilities for the protection and conservation of groundwater resources;
- to provide geological and hydrogeological information for the planning process, so that potentially polluting developments can be located and controlled in an environmentally acceptable way.
- to integrate the factors associated with groundwater contamination risk, to focus attention on the higher risk areas and activities, and provide a logical structure within which contamination control measures can be selected.

The scheme is not intended to have any statutory authority now or in the future; rather it should provide a framework for decision-making and guidelines for the statutory authorities in carrying out their functions. As groundwater protection decisions are often complex, sometimes requiring detailed geological and hydrogeological information, the scheme is not prescriptive and needs to be qualified by site-specific considerations.

COMPONENTS OF THE GROUNDWATER PROTECTION SCHEME

There are two main components:

i) A land surface zoning map (or maps)(groundwater protection map), which encompasses the hydrogeological elements of risk.

ii) Control measures or a code of practice for existing and new potentially polluting activities, which encompasses both the contaminant loading element of risk and planning/preventative measures as a response to the risk.

The final stage in the production of the groundwater protection scheme involves the integration of both components.

LAND SURFACE ZONING FOR GROUNDWATER PROTECTION

GENERAL STRATEGY

Land surface zoning provides the general framework for the groundwater protection scheme. The outcome is a map, which divides any chosen area into a number of groundwater protection zones according to the degree of protection required. Different systems of zoning protection areas are in use. Some are simple with little hydrogeological input; for instance, using arbitrary fixed radii around sources. Others are sophisticated and are based on appreciable hydrogeological data and analysis. The level of sophistication usually depends on the level of data and resources (time, money and staff) available. Although the simple schemes are a good "first step", for a scheme to be defensible it should be founded on hydrogeological concepts.

There are three main elements to land surface zoning:

- Division of the entire land surface on the basis of the vulnerability of the underlying groundwater to contamination
- Areas surrounding individual groundwater sources; these are termed source protection areas.
- Areas sub-divided according to the value of the groundwater resources or aquifer category; these are termed resource protection areas

GROUNDWATER VULNERABILITY CATEGORIES

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

The vulnerability of groundwater depends on the time of travel of infiltrating water (and contaminants), on the relative quantity of contaminants that can reach the groundwater and on the contaminant attenuation capacity of the geological materials. 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. The travel time, attenuation capacity and quantity of contaminants are a function of the following natural geological and hydrogeological attributes of any area:

(i) the subsoils that overlie the groundwater;
(ii) the recharge type - whether point or diffuse;
(iii) the thickness of the unsaturated zone below the point at which the contaminant is introduced;
(iv) in the case of diffuse pollution sources, the topsoil.

In general, little attenuation of contaminants occurs in bedrock in Ireland because flow is almost wholly via fissures. Consequently, the subsoil - sands, gravels, glacial tills (or boulder clays), lake and alluvial silts and clays, peat - are the single most important natural feature in influencing groundwater vulnerability and groundwater contamination prevention. Groundwater is most at risk where the subsoils are absent or thin and, in karstic areas, where surface streams sink underground at swallow holes.

The geological and hydrogeological characteristics can be examined and mapped, thereby providing a groundwater vulnerability assessment for any area or site. Four groundwater vulnerability categories are used by the GSI - **extreme, high, moderate** and **low**. Examples of each are given in Table 1. These ratings are not scientifically precise; they are based on pragmatic judgements, experience and limited technical and scientific information. However, provided the limitations are appreciated, vulnerability assessments are an important element when considering the location of potentially polluting activities. The ranking of vulnerability does not take into consideration the biologically-active soil zone, as contaminants from point sources are usually applied below this zone, often at depths of at least 1m.

Table 1 : Examples of Vulnerability Ratings

VULNERABILITY RATING	HYDROGEOLOGICAL SETTING
Extreme	Outcropping bedrock or where bedrock is overlain by shallow (<3m) subsoil
High	Bedrock overlain by 3-10m of intermediate permeability subsoil such as sandy till or 3-5m of low permeability subsoil such as clayey till, clay or peat
Moderate	Bedrock overlain by >10m of sandy till or 5-10m of clayey till, clay or peat
Low	Bedrock overlain by >10m of clayey till, clay or peat

(from Daly and Warren, 1994)

The vulnerability concept and vulnerability maps are an important part of groundwater protection schemes and are an essential element in decision-making on the location of potentially polluting activities. Firstly, the vulnerability rating for any area indicates and is a measure of the likelihood of contamination. Secondly, the vulnerability map assists in ensuring that the groundwater protection scheme is not unnecessarily restrictive on human economic activity. Thirdly, the vulnerability map helps in the choice of preventative engineering measures and enables major developments, which have a significant potential to contaminate, to be located in relatively low vulnerability and therefore in relatively low risk areas, from a groundwater point of view.

In summary, the entire land surface is divided into four vulnerability categories - extreme (E), high (**H**), moderate (**M**) and low (**L**) - based on the geological and hydrogeological factors described above and this subdivision is shown on a groundwater vulnerability map.

GROUNDWATER SOURCE PROTECTION AREAS

General

Groundwater sources, particularly public, group scheme and industrial supplies, are of critical importance in any region. Consequently, the objective of source protection areas (SPAs) is to provide an additional element of protection, by placing tighter controls on activities within all or part of the zone of contribution (ZOC) of the source. Three source protection areas are recommended for delineation:

- Source Site;
- Inner Protection Area;
- Outer Protection Area, encompassing the source catchment area or zone of contribution.

Delineation of Source Protection Areas

The orientation, shape and size of the Source Site is based on practical, non-technical considerations. In delineating the Inner and Outer Protection Areas areas, there are two broad approaches: firstly, using arbitrary fixed radii, which do not incorporate hydrogeological considerations; and secondly, a scientific approach using hydrogeological information and analysis, in particular the hydrogeological characteristics of the aquifer, the direction of groundwater flow and the pumping rate.

Where the hydrogeological information is poor and/or where time and resources are restricted, the simple zonation approach using the arbitrary fixed radius method is a good first step that requires little technical expertise. However, it can both over- and under-protect. It usually over-protects on the downgradient side of the source and may under-protect on the upgradient side, particularly in karst areas. It is particularly inappropriate in the case of springs where there is no part of the downgradient side in the zone of contribution. Also, the lack of a scientific basis reduces its defensibility as a method.

There are several hydrogeological methods for delineating SPAs. They vary in complexity, cost and the level of data and hydrogeological analysis required. Four methods, in order of increasing technical sophistication, are used by the GSI:

- Calculated Fixed Radius
- Analytical Methods
- Hydrogeological Mapping
- Numerical Modelling

Each method has limitations. Even with relatively good hydrogeological data, the heterogeneity of Irish aquifers will generally prevent the delineation of definitive SPA boundaries. Consequently, the boundaries must be seen as a guide for decision-making, which can be reappraised in the light of new knowledge or changed circumstances.

Source Site
This is the innermost protection area, which includes the source and usually the operational activities associated with water supply. It should be under the ownership and control of the groundwater abstractor. The area should be fenced off and the boundaries should be at least 10m from the source. All potentially polluting activities not directly related to the production of drinking water should be prohibited and care should be taken that the operational activities do not cause pollution.

Inner Protection Area
This zone is designed to protect against the effects of human activities that might have an immediate effect on the source and, in particular, against microbial pollution. The area is defined by a 100-day time of travel (TOT) from any point below the water table to the source. (The TOT varies significantly between regulatory agencies in different countries. The 100-day limit is chosen for Ireland as a relatively conservative limit to allow for the heterogeneous nature of Irish aquifers and to reduce the risk of pollution from bacteria and viruses, which in some circumstances can live longer than 50 days in groundwater.)

In karst areas where conduit flow is dominant, the TOT approach is not applicable, as there are large variations in permeability, high flow velocities and a low level of predictability.

If it is necessary to use the arbitrary fixed radius method, a distance of 300m is chosen. A semi-circular area is used for springs. The distance may be increased for sources in karst (cavernous) aquifers and reduced in granular aquifers and around low yielding sources.

Outer Protection Area
This zone covers the zone of contribution (ZOC) (or complete catchment area) of the groundwater source. It is defined as an area needed to support an abstraction from long-term groundwater recharge (the proportion of effective rainfall that infiltrates to the water table). The abstraction rate used in delineating the zone will depend on the views of the source owner. The GSI currently increases the

maximum daily abstraction rate by 50% to allow for possible future increases in abstraction and for expansion of the ZOC in dry periods.

If the arbitrary fixed radius method is used, a distance of 1000m is chosen with, in some instances, variations in karst aquifers and around springs and low-yielding wells.

GROUNDWATER RESOURCE PROTECTION AREAS

For any region, the area outside the source protection areas is subdivided, based on the value of the resource and the hydrogeological characteristics, into eight resource protection areas:

Regionally Important (R) Aquifers

(i) Karstified limestone (where conduit flow is dominant) (**Rk**)
(ii) Fractured bedrock (**Rf**)
(iii) Extensive sand/gravel (**Rg**)

Locally Important (L) Aquifers

(i) Sand/gravel (**Lg**)
(ii) Generally Moderately Productive (**Lm**)
(iii) Moderately Productive only in Local Zones (**Ll**)

Poor (P) Aquifers

(i) Generally Unproductive except for Local Zones (**Pl**)
(ii) Generally Unproductive (**Pu**)

GROUNDWATER PROTECTION ZONES

The matrix in Table 2 below gives the result of integrating the three elements of land surface zoning (vulnerability categories, source protection areas and resource protection areas) – a possible total of 12 source protection zones and 24 resource protection zones. In practice this is achieved by superimposing the vulnerability map on source protection area maps and on the aquifer map. Each zone is represented by a code e.g. **Rf/M**, which represents areas of regionally important fissured aquifers where the groundwater is moderately vulnerable to contamination. All of the hydrogeological settings represented by the zones may not be present in each local authority area.

Table 2 Matrix of Groundwater Protection Zones

VULNERABILITY RATING	SOURCE PROTECTION			RESOURCE PROTECTION					
				Regionally Imp		Locally Imp.		Poor Aquifers	
	Site	*Inner*	*Outer*	*Rk*	*Rf/Rg*	*Lm/L*	*Ll*	*Pl*	*Pu*
Extreme (E)	SS/E	SI/E	SO/E	Rk/E	Rf/E	Lm/E	Ll/E	Pl/E	Pu/E
High (H)	SS/H	SI/H	SO/H	Rk/H	Rf/H	Lm/H	Ll/H	Pl/H	Pu/H
Moderate (M)	SS/M	SI/M	SO/M	Rk/M	Rf/M	Lm/M	Ll/M	Pl/M	Pu/M
Low (L)	SS/L	SI/L	SO/L	Rk/L	Rf/L	Lm/L	Ll/L	Pl/L	Pu/L

The zones in Table 2 can be shown on hand-drawn maps, maps drawn using AutoCad or, preferably, by using a GIS. A GIS has the advantages that a map can readily be drawn for any particular activity - landfills, for example - and the product looks good. However care needs to be taken that the GIS results are based on adequate data and that GIMGO (garbage in, multi-coloured garbage out) does not apply!

As source protection zones need to be shown on large scale maps - 1:25,000 or 1:10,560 - two sets of maps are necessary, one dealing with source protection and the second with resource protection. For resource protection, map scales of 1:63,360 or preferably 1:50,000 are recommended.

CONTROL OF POLLUTING ACTIVITIES

CODE OF PRACTICE

The control of groundwater contamination sources is by means of a code of practice which lists the degree of acceptability of potentially polluting activities for each zone and describes the recommended controls for both existing and new activities. Both the code of practice itself and the method of summarising and utilising it varies from country to country. It is often shown by way of a level of response or restriction, which is applied to each potentially polluting activity or group of activities, with the level of response depending on the different elements of risk - the vulnerability, the value of the groundwater (with sources being more valuable then resources and regionally important aquifers more valuable than locally important and so on) and the contaminant loading.

Four levels of response (**R**) to the risk of a particular potentially polluting activity are recommended for the Irish situation:

R1	Acceptable
R2$^{a,b,c,...}$	Acceptable in principle, subject to conditions in note a,b,c, etc. (The number and content of the notes will vary for each zone and for each activity).
R3$^{m,n,o,...}$	Not acceptable in principle; some exceptions may be allowed subject to the conditions in note m,n,o, etc.
R4	Not acceptable

These levels of response can be applied either to specific activities or to groups of activities.

Decisions on the response category and the code of practice for potentially polluting developments are the responsibility of the statutory authorities, in particular, the local authorities and the EPA; although it is advisable that the decisions should follow from a multi-disciplinary assessment process involving hydrogeologists.

INTEGRATION OF GROUNDWATER PROTECTION ZONES AND CODE OF PRACTICE

The integration of the groundwater protection zones and the code of practice is the final stage in the production of the groundwater protection scheme. The approach used by the GSI is illustrated for a hypothetical potentially polluting activity in the matrix in Table 3 below:

The matrix encompasses both the geological/hydrogeological and the contaminant loading aspects of risk assessment. In general, the arrows (→ ↓) indicate directions of decreasing risk, with the ↓ arrow showing the decreasing **likelihood of contamination** and the → arrow showing the direction of **decreasing consequence**. The **contaminant loading** aspect of risk is indicated by the activity type in the table title.

The **response** to the risk of groundwater contamination is given by the response category allocated to each zone and by the site investigations and/or controls and/or protective measures described in notes a,b,c,d,m n and o. For example, the response to a proposal to locate a landfill site in Zone Rk/E (the highest risk zone outside of source protection zones) could be R4, i.e. 'not acceptable'; whereas the response for a septic tank system might be $R3^2$, i.e. 'not generally acceptable, unless it is shown by investigation and assessment that the risk to groundwater is low or can be significantly reduced by the use of engineered preventative measures, such as on-site treatment systems'. The response to locating a landfill site in Zone Ll/M could be $R2^3$, i.e. 'acceptable in principle, engineering measures may be needed to provide adequate containment and special attention should be given to shecking for the presence of high permeability zones'. More comprehensive details in using the scheme are given in Daly (1995).

It may appear at first glance that there are too many zones - 12 for source protection and 24 for resource protection. However, in practice the number of areas with the same control requirements will be much less for any particular activity. Also, the number of hydrogeological situations represented by each zone may not be present in each local authority area.

Table 3 Groundwater Protection Scheme Matrix for Activity X

VULNERABILITY RATING	SOURCE PROTECTION			RESOURCE PROTECTION						
				Regionally Imp		Locally Imp.		Poor Aquifers		
	Site	*Inner*	*Outer*	*Rk*	*Rf/Rg*	*Lm/Lg*	*Ll*	*Pl*	*Pu*	
Extreme (E)	R4	R4	R4	R4	R4	$R3^{m}$	$R2^{d}$	$R2^{c}$	$R2^{b}$	↓
High (H)	R4	R4	R4	R4	$R3^{m}$	$R3^{n}$	$R2^{c}$	$R2^{b}$	$R2^{a}$	↓
Moderate (M)	R4	R4	$R3^{m}$	$R3^{m}$	$R2^{d}$	$R2^{c}$	$R2^{b}$	$R2^{a}$	R1	↓
Low (L)	R4	$R3^{m}$	$R3^{o}$	$R2^{d}$	$R2^{c}$	$R2^{b}$	$R2^{a}$	R1	R1	↓
	→	→	→	→	→	→	→	→	→	

In considering the scheme, it is essential to remember that (a) the scheme is intended to provide guidelines for the location of developments and that (b) delineation of the groundwater protection zones is dependent on the data available and consequently may not be accurate in places. However, the intention of the scheme is that the statutory authorities should apply it in decision-making on the basis that the best available data is being used. The onus is then on the developer to provide new information which could enable the zonation to be altered and improved and, in certain circumstances, the proposed planning decision to be changed.

CONCLUSIONS

- Groundwater protection schemes are an essential means of enabling local authorities to take account of i) the potential risks to groundwater resources and sources and ii) geological and hydrogeological factors, when considering the location of potentially polluting developments; consequently, they are now an essential means of preventing groundwater contamination.

- If planning decisions based on a groundwater protection scheme are to be readily defensible, it is important that the scheme should be founded on hydrogeological concepts and on a sufficient degree of geological and hydrogeological information.

- Groundwater protection schemes should not be seen as a panacea for solving all groundwater contamination problems. In practice their use needs a realistic and flexible approach. The maps have limitations because they generalise (with the degree of generalisation depending on data availability) variable and complex geological and hydrogeological conditions. Consequently, the proposed scheme is not prescriptive and needs to be qualified by site-specific considerations and investigations. The investigation requirements depend mainly on the degree of hazard provided by the contaminant loading and , to a lesser extent, on the availability of hydrogeological data.

- The scheme has the following uses:
  - it provides a hierarchy of levels of risk and, in the process, assists in setting priorities for technical resources and investigations.
  - it contributes to the search for a balance of interests between groundwater protection issues and other special and economic factors.
  - it can be adapted to include risk to surface water.
  - it acts as a guide and provides a 'first-off' warning system before site visits and investigations are made.
  - it shows generally suitable and unsuitable areas for potentially hazardous developments such as landfill sites and piggeries.
  - by controlling developments and enabling the location of certain potentially hazardous activities in lower risk areas, it helps ensure that the pollution acts are not contravened.
  - it can be used in preparing Emergency Plans, assessing environmental impact statements and the implications of EU directives, planning and undertaking groundwater monitoring networks and in locating water supplies.

- The groundwater protection scheme outlined in this paper, when properly used, is a valuable tool in helping to achieve the objective of sustainable water quality management, as required by national and EU policies.

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THE ROLE OF MODELLING IN GROUNDWATER PROTECTION

P.JOHNSTON
Dept of Civil, Structural and Environmental Engineering, Trinity College

ABSTRACT

Groundwater is an important source of water supply in Ireland and the sustainability of that resource is basic to the long term needs of national economic development. The cost effective approach to achieving sustainability is through environmental protection of both the groundwater resource and individual sources such as wells, springs and boreholes. While sustainable yields from sources are readily ascertained, the quality of groundwater is showing cause for concern. Levels of protection of both sources and resources (aquifers) may be achieved through assessment of the corresponding risks posed by different hazards (potentially polluting activities). Applying the concepts of risk to the protection of aquifers requires the determination of spatial vulnerability of the aquifers to the potential hazards. Vulnerability may be assessed through the use of simple models of the hydrogeology which, in turn, lend themselves to incorporation in GIS systems throgh which final vulnerability maps may be produced. Source protection involves determination of Zones of Contribution from which potentially polluting activities may be excluded through landuse planning. Conservative estimates of ZOC's may be made through models of the groundwater hydraulics in the vicinity of the source. Such models necessarily depend upon appropriate conceptualization of the hydrogeological system. In these contexts, models represent an objective means of using available data to determine levels of protection but they should not be a replacement for the required understanding of the hydrogeological regime.

INTRODUCTION

As part of the hydrological cycle, groundwater is, by its nature, a renewable resource. Moreover, groundwater is a major source of water supply in Ireland, being tapped through boreholes, wells and springs. Sustainability of that resource is fundamental to both national and local economic development. That sustainability, in turn, may be assessed in terms of both quantity (flow) and quality (biological and chemical).

The groundwater regime in Ireland is characterized by relatively high water tables, recharged by frequent rainfall infiltrating through a thin soil cover and effectively draining through the stream and river network. In this context, a sustainable yield for a source is relatively straightforward to ascertain and, although not often determined, the risk of failure is usually small. On the other hand, the quality of the water from many sources is giving cause for increasing concern. The principal threats to groundwater quality arise from 'point' sources which may include agricultural slurries, septic tank soakaways, waste disposal sites and contaminated land (Daly,1995). Potential threats to quality exist in more diffuse contaminant sources such as agricultural fertilizing and the land spreading of sludges. All these sources of contamination, actual or potential, can be said to present a 'hazard' to an aquifer or a groundwater source although mobilization of the contaminant depends on rainfall and the subsurface flow regime.

It may be argued that the most cost-effective way of sustaining the natural quality of a groundwater is through prevention of contamination - that is, by protecting the aquifer or source against the hazard rather than by treating any pollution at the point of abstraction. Protection, in this context, is in terms of landuse planning whereby rules are devised for the siting of potential hazards such as landfills or septic tanks. The guidelines set out by the Geological Survey of Ireland are a good example. Models are a valuable tool in the implementation of such guidelines and are the subject of this paper.

PROTECTION AND RISK

Protection is a relative concept in the sense that there are implied degrees of protection. An increasing level of protection is equivalent to reducing the risk of damage to the protected quantity, that is, groundwater. Moreover, choosing an appropriate degree of protection for an aquifer or source necessarily involves placing a relative value on the protected quantity. In decreasing order, levels of protection may range from

- Exclusion or total removal of a (potential) hazard (eg prohibition of all potentially contaminating activity from the vicinity of a source)
- Controlling or modifying the hazard to reduce the risk to the aquifer or source (eg specification of liners for a landfill)
- Do nothing - ie no protection and reliance on natural processes of attenuation and dilution to reduce contaminant concentrations to 'acceptable' levels.

The fact that the last option has been perceived not to work has raised the need for an aquifer protection policy. Models can be used in helping to quantify these concepts of protection and as an aid in their pragmatic implementation. Current practice is to evaluate levels of protection in terms of risk and to differentiate protection policies for groundwater resources (aquifers) from those for groundwater sources (wells and springs).

To provide the appropriate framework for modelling, a specific definition of risk as applied to groundwater is required:

RISK	=	PROBABILITY OF AN EVENT	X	CONSEQUENTIAL DAMAGE
		(or level of activity causing potential pollution)		(measure of the consequence of the polluting activity)
	=	HAZARD	X	VULNERABILITY

- Hazard relates to the level or scale of the potentially polluting activity, incorporating the idea of a relative scale of pollution threat as well as the concept of the relative value of the groundwater being threatened (eg a regionally important, locally important or poor aquifer as specified by Geological Survey guidelines). Thus, a leaching landfill presents a significant hazard on a major aquifer whereas the occasional fertilizing of a field presents a much smaller hazard. In modelling terms, a hazard is often represented by a relative scale index.
- Vulnerability relates to the intrinsic characteristics of the natural system (hydrology and hydrogeology) conditioning the sensitivity of the aquifer to being polluted. An aquifer with a cover of sandy gravel is clearly more vulnerable to a pollution hazard than an aquifer with a cover of several metres of boulder clay. Vulnerability may be specific to a particular contaminant but commonly it is assumed that a contaminant migrating at the same rate as the soil and ground water flow represents the 'worst', design case. In other words vulnerability is usually quantified in terms of hydrogeological characteristics only and does not take account of specific contaminant properties.

Thus, in modelling terms, vulnerability may assume varying degrees of complexity, ranging from a simple measure of soil cover thickness to more complex equations of soil physics and groundwater flow.

This relationship for risk provides the necessary framework for the use of appropriate modelling techniques. The application to groundwater protection may be summarized in the following diagrammatic form:

	CONTAMINANT	————————————→	**TARGET**
	SOURCE	**PATHWAY**	
=	HAZARD	VULNERABILITY	AQUIFER or G/W SOURCE

In either resource protection or source protection, the approach is, initially, to ignore the nature of the hazard and to assess the risk presented by the combination of the pathway/vulnerability and the nature of the aquifer or groundwater source. In the numerical calculation of risk, it could be said that the hazard has a value of unity.

RESOURCE PROTECTION

The approach to resource protection is to assess the vulnerability of the aquifer in terms of its relative value and a characterization of the pathways to the groundwater, irrespective of the potential hazard in the first instance. At a given geographical point, the risk to the groundwater quality, therefore, is calculated by combining a measure of vulnerability with a measure of the worth of the aquifer. The worth of the aquifer may be assessed as a simple linear scale index with a major aquifer having a low integer value and a poor aquifer having a high value. The pathways to the groundwater may be characterized in different ways, depending on available data. . A simple way would be to use an estimate of the thickness of subsoil or depth to the water table. A more effective model is to characterize the pathways by an estimate of notional travel time to the groundwater, estimated by dividing the depth to water table by the hydraulic conductivity. A measure of risk may be estimated by multiplying this measure of vulnerability by the aquifer index - the greater the value, the greater the risk to the aquifer. These values are clearly spatially dependent and plotted values of such estimates can be contoured or bounded to delineate areas of relative risk so as to aid in landuse planning.

These simple models are essentially quantifications of the vulnerability ratings discussed in the Geological Survey guidelines. Such models can be constructed by combining mapped layers of data (eg maps of hydraulic conductivity, depth to water table and of the aquifer types) and therefore lend themselves to the use of Geographical Information Systems (GIS). In this way, layers of information can readily be changed or weighted in order to suit particular needs in terms of hydrogeology or planning. Such systems can also be adapted to help in the siting of particular hazards such as landfills by adding further layers of data to the GIS system, characterizing the nature of the hazard.

By their nature, maps of data required to construct even simple models of aquifer vulnerability are data hungry. Consequently, when applying such schemes in practice, data may be sparse and the resulting vulnerability map subject to considerable uncertainty. At best, the model employed is a way of objectively combining the data which is available but the result may require interpretation in the light of other less quantifiable hydrogeological/hydrological information. Furthermore, any such map of vulnerability is necessarily a guide and does not preclude the need for specific site investigation to confirm any indications gleaned from it

This need for caution and interpretation is particularly apt in areas of karstic or fissured limestone. Straightforward mapping of vulnerability with available information may not appropriately represent the presence of narrow subsurface fissure systems. Such zones may be allowed for by using arbitrarily imposing suitable conditions in compiling the final vulnerability map.

SOURCE PROTECTION

Similarly to the protection of the resource, the protection of a groundwater source is approached by considering the risks to the quality of that source. Because a source is an active abstraction, it is presumed that the maximum level of protection is required. In contrast to resource protection, relative risks are not evaluated, at least not to begin with. The initial approach is to identify all pathways to the source, irrespective of relative vulnerability or any potential hazard. The concept is one of reducing risks of contamination to the source to a minimum. Thus, this concept usually implies the determination of an area, known as the Zone of Contribution (ZOC), about the source, from which most hazards are to be excluded, through landuse planning. The ZOC represents an 'all risks' protection zone.

However, the ZOC may be modified (that is, the area reduced) by accepting very low risks to the source arising from unspecified potential contamination originating from certain subzones within the ZOC. These subzones are usually delineated by determination of those pathways with potential travel times to the source above a certain specified limit (eg 100 days). Thus, certain activities, in terms of land use, may be permitted which represent hazards which do not significantly increase the risk to the source when combined with the long pathways.

In terms of the contaminant source-pathway-target conceptual model, the problem is to delineate the area traced out by all possible contaminant pathways to the target groundwater source, truncated by times of travel presumed to represent very low risk. The ZOC so delineated should be conservative in that the hypothetical contaminant is presumed to travel at the same velocity as the subsurface water - no account is taken of any contaminant properties. Given this conceptual framework, a ZOC is essentially defined on the basis of groundwater hydraulics, not contaminant transport. A numerical model can, therefore, readily be used to determine the ZOC under specified hydrological conditions. The requirements of such a model are to represent the behaviour of the flow system defined as operating in the vicinity of the groundwater source. An important characteristic of this representation is that the groundwater source itself influences the flow system. In other words, the extent of the ZOC is dependent upon the strength of the source (discharge) - the greater the abstraction rate, the greater the area contributing to the source. A model is often the only practical means of determining these relationships, albeit under somewhat simplified hydrogeological conditions.

MODELLING FOR SOURCE PROTECTION

While a model is inevitably a simplified representation of a more complex reality, its utility lies in still being able to reproduce the essential behavioural characteristics of the real system. In this way, a model representing the behaviour of a groundwater source in a given hydrogeological system can be used to predict the nature or extent of the hydraulic influence of that source and, thereby, its zone of contribution requiring protection can be determined. Nevertheless, in spite of this predictive mode, the principal value of a model in this context is as an aid in the understanding of the behaviour and nature of the groundwater system under study. That is, its main utility is in an interpretive or generic mode, by which a model is used to test or investigate the validity of a particular hydrogeological conceptualization. The steps in the modelling process are well established (Anderson and Woessner,1992):

- Develop a conceptual model of the source and system under study
- Select or construct appropriate equations and computer code to represent that conceptual model
- Collect appropriate field data to support the design of the model
- Calibrate the model against field data, eg an observed water table or discharge
- Readjust or modify the model, as required in the light of comparison of its behaviour against field data or observations
- Sensitivity analysis, to determine the response characteristics of the model - that is, the parameters most likely to control its behaviour
- Simulation and prediction of the required outcome

The model, as a numerical, computerized representation of the hydrogeological system, is not an end in itself. It does not replace the inherent understanding of the hydrogeology in a given situation - indeed, a numerical model starts with whatever understanding currently exists, that is, a conceptual model. The numerical model is only a mathematical representation of that conceptualization. Given that hypothesis, a computer model then allows certain 'what if' questions to be answered. For example, how does the zone of contribution change if the pumping rate of the source is increased? Moreover, the implications of a particular conceptual model can be explored with a numerical model and, thus, the validity or plausibility of that original conceptualization can be evaluated.

Modelling the behaviour of a particular groundwater source in a given hydrogeological system, thereby delineating a zone of contribution, requires a specific conceptualization or description of the groundwater system and its parameters. Different levels of simplification of the conceptual model (usually as a result of corresponding data availability) invariably lead to different predictions in the shape and extent of a ZOC. This problem does not imply that the simpler models are invalid, more that the predictions are likely to have greater uncertainty associated with them. In order of increasing complexity, certain common conceptualizations of hydrogeological behaviour will give rise to predictable shapes of ZOC, as illustrated in the accompanying figures:

- If almost no hydrogeological data exists for a particular groundwater source, the model may be correspondingly simple, starting with an assumed, fixed radius of influence for the source, determined as a result of observations elsewhere in the region or aquifer (figure 3).
- A very simple hydrogeological conceptualization may be assumed with a little more data available. Typically, the aquifer may be assumed to be homogeneous, isotropic, and notionally confined with fixed, horizontal upper and lower boundaries. If the groundwater in the aquifer is assumed to be static with a horizontal water table and a value of aquifer hydraulic conductivity may be estimated, the ZOC will be a circle centred on the well. The diameter of the circle may be determined from a simple water balance (figure 3) or, if a little more data is available (eg hydraulic conductivity, aquifer thickness,well diameter) from using Darcy's equation applied to well hydraulics. The model, in this case, is an analytical solution to the equations of groundwater flow. However, the model can be used to determine a relationship between pumping rate and the radius of the ZOC.
- If further complexity is added to the model above, in the form of a uniform, regional groundwater flow, the shape of the ZOC changes from a simple circle to an open ended shape, open in the upgradient direction (figure 1). Nevertheless, the conceptual model of the groundwater hydraulics remains simple - the geometry of the aquifer is as before and the aquifer is presumed to have a single value for hydraulic conductivity. The water table is now presumed to be a plane surface but sloping, with a single value for its gradient. Again, an analytical solution exists for this simple conceptualization and it has been incorporated into commercially available software such as the Well Head Protection Area model from the US Environmental Protection Agency (figure 2). It is at this level of complexity that the ZOC may have to be truncated to produce source protection subzones based on travel times.

- If direct but uniform recharge (net rainfall) across the aquifer is added to the complexity of the model, the shape of the ZOC remains similarly open ended but tends to widen at the upgradient end. At this stage of complexity, the required solution to the groundwater flow equations requires a numerical solution, albeit with commercially available software. Nevertheless, the aquifer is still assumed to be homogeneous and its parameters (transmissivity and storage coefficient) single valued.
- The current limit to complexity, often now assumed in a conceptual model, incorporates the ability to vary the aquifer parameters with position. In other words, the aquifer is assumed to be heterogeneous and may also be anisotropic. Solution of the groundwater flow equations clearly demands computerized solution techniques and the geometry of the resulting ZOC is correspondingly more complex (figure 4). However, such complex conceptualizations can be extremely data hungry, demanding specific knowledge of the spatial variability of transmissivity across the aquifer. If such data is not available (usually the case), the required inputs to the model are estimated or the model itself can be used to try and identify appropriate values through fitting the model to whatever field data is available. Clearly, any prediction of a ZOC in these circumstances will be non-unique and usually considerable uncertainty attaches to such predictions.
- In the light of such data scarcity and resulting uncertainty when using such models, current practice favours the introduction of buffer zones around the predicted ZOC. The delineation of these buffer zones partly depends on the outcome of a sensitivity analysis using the model and partly depends on estimates of uncertainties in the data themselves (eg in the values of water level measurements). Moreover, such arbitrary buffer zones may be introduced to account for known hydrogeological characteristics (eg fissured zones) which may not be expressly represented in the model (eg in karstic limestones in Waterford as shown in figure 5).

All of these models, variants of which are in common use in studies of aquifer protection in Ireland, rest on the assumption of steady state hydraulics in a locally homogeneous porous medium. In other words, fractures are not expressly modelled but are treated as part of a larger homogeneous medium,as a so-called 'equivalent porous medium'. Although some attempts have been made to represent fracture or fissure systems specifically in models, their routine use is largely inhibited by the lack of appropriate observational data.

CONLUSION

Sustainability of groundwater resources and, specifically, groundwater sources, in Ireland is essential to national economic wellbeing. Usually, sustaining resources in terms of flow is not a problem but sustaining quality has to be addressed through policies for environmental protection, as set out by the Geological Survey of Ireland. Strategies for environmental protection both of groundwater resources as well as sources (wells, springs and boreholes) are approached through the concept of evaluating risk to the protected quantity. Resource protection is implemented through spatial estimates (maps) of aquifer vulnerability which can be used in landuse planning. Source protection is approached by designating different levels of Source Protection Area around the well or spring, based on perceived corresponding levels of risk. In both cases, numerical computer models are valuable tools in assessing levels of vulnerability or in designating SPA's. Nevertheless, the model is necessarily only as good as the conceptualization of the hydrogeology that underpins it and is not a replacement for the required hydrogeological understanding. The value of a model lies in its role of objectively employing the available data in order to reach an evaluation or prediction. Results must be interpreted in the light of the inevitable uncertainty caused by poor data availability or possibly inappropriate conceptualization of the hydrogeology. In spite of the caveats, models are an essential aid in the determination of environmental risk and strategies for sustainability.

ACKNOWLEDGEMENTS

The practical application of the concepts presented in this paper were largely undertaken by MSc students, particularly of Trinity College Dublin, in collaboration with the Geological Survey of Ireland. Particular contributions were made by Jennifer Deakin and Donal McDaid. Discussions with Donal Daly of the Geological Survey of Ireland, concerning the development of guidelines for schemes for aquifer protection were an important influence in the preparation of the paper

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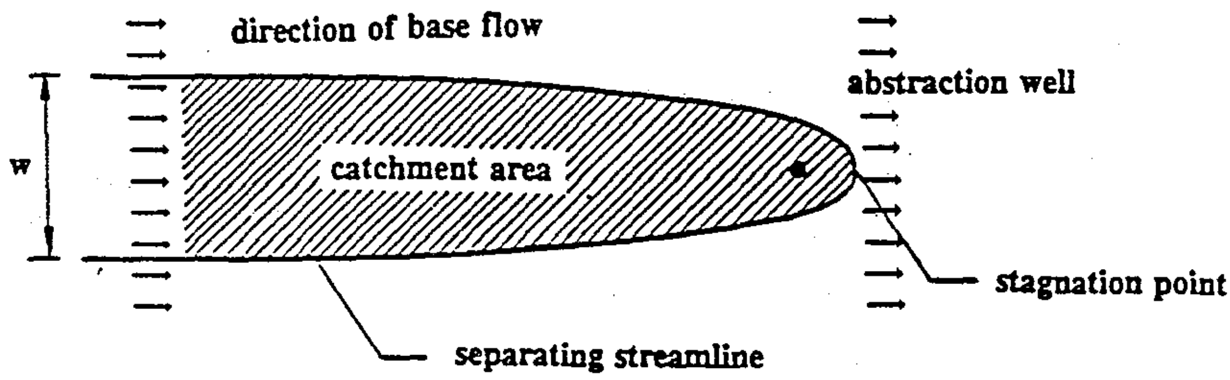

FIGURE 1 : SKETCH OF A ZONE OF CONTRIBUTION (ZOC) OR SOURCE PROTECTION AREA (SPA) DEFINED BY THE MODEL OF A PUMPING WELL IN A UNIFORM FLOW

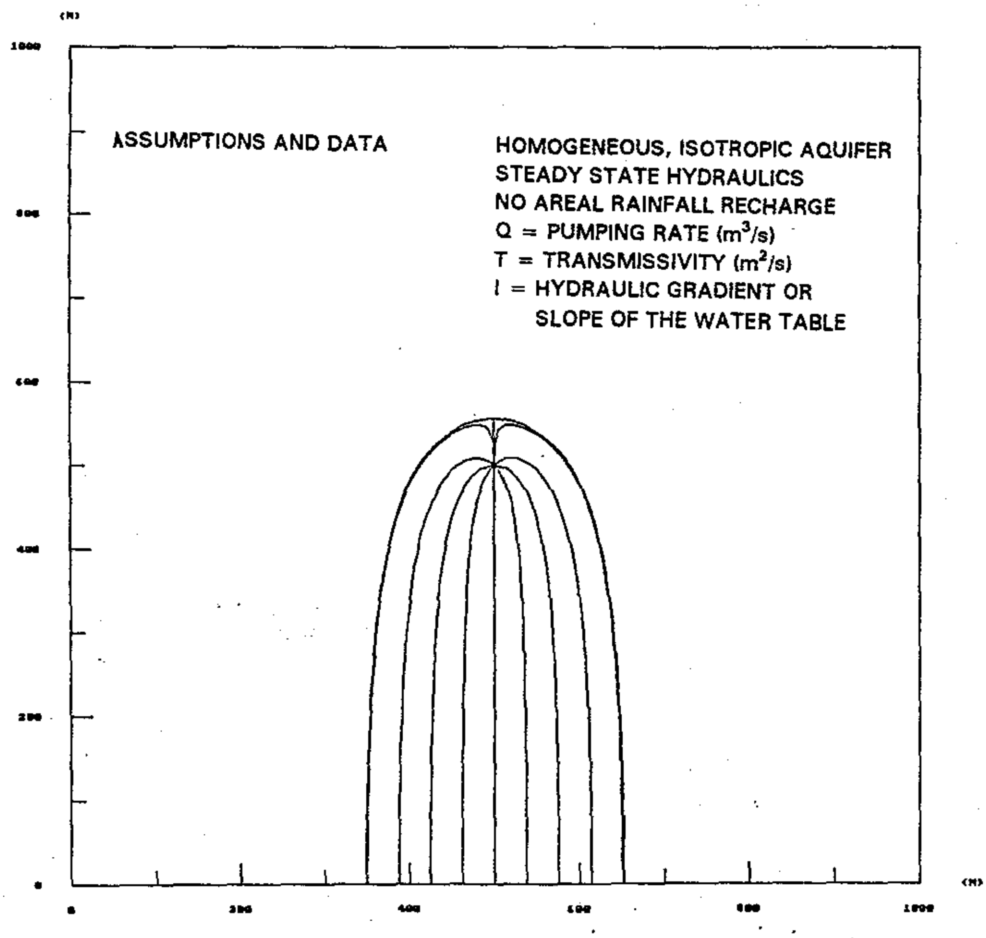

FIGURE 2 : CORRESPONDING OUTPUT OF THE US EPA MODEL FOR WELL HEAD PROTECTION AREAS (WHPA)

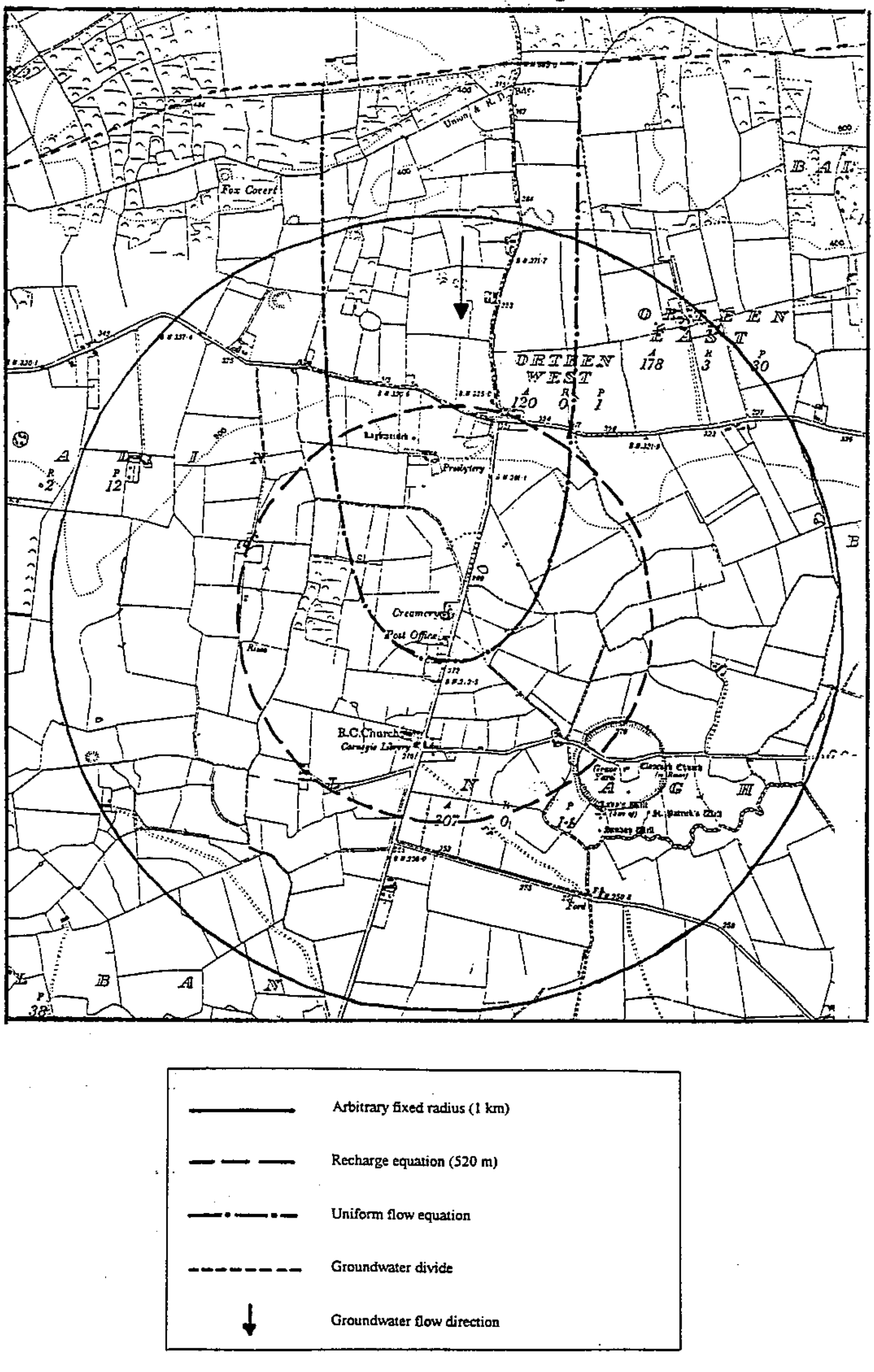

FIGURE 3 : COMPARISON OF SIMPLE MODELS FOR DEFINING A ZOC FOR A CREAMERY WELL IN COUNTY LIMERICK (after J.Deakin,1995)

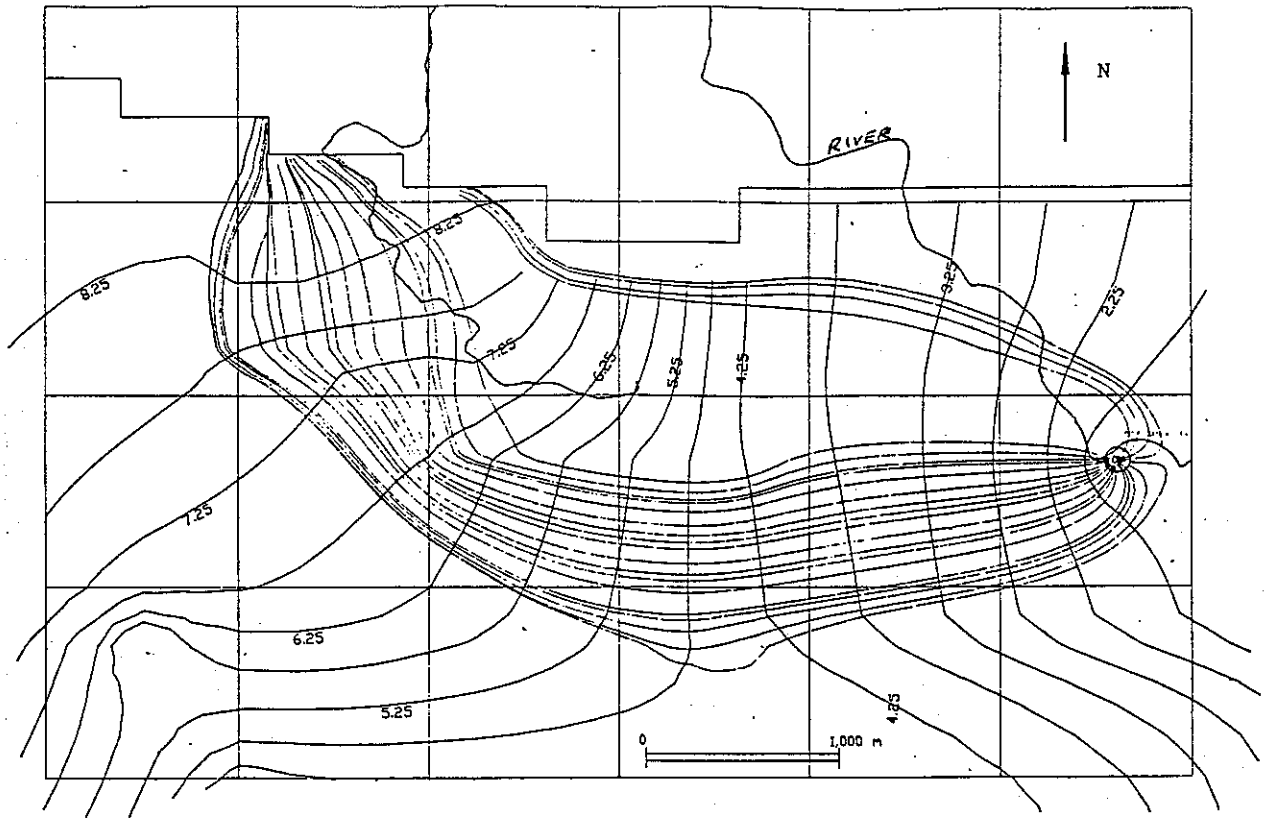

FIGURE 4 : A ZOC DETERMINED USING A TWO DIMENSIONAL FINITE DIFFERENCE SOLUTION (FLOWPATH MODEL) FOR THE GROUNDWATER FLOW EQUATIONS. BALLINAMUCK SPRING SOURCE (7194m^3/day) IN A FISSURED LIMESTONE AQUIFER IN COUNTY WATERFORD

DATA REQUIRED : PUMPING RATE, Q; AND DISTRIBUTED ESTIMATES OF TRANSMISSIVITY,T, WATER TABLE ELEVATIONS AND RECHARGE RATES (RAINFALL - EVAPOTRANSPIRATION)

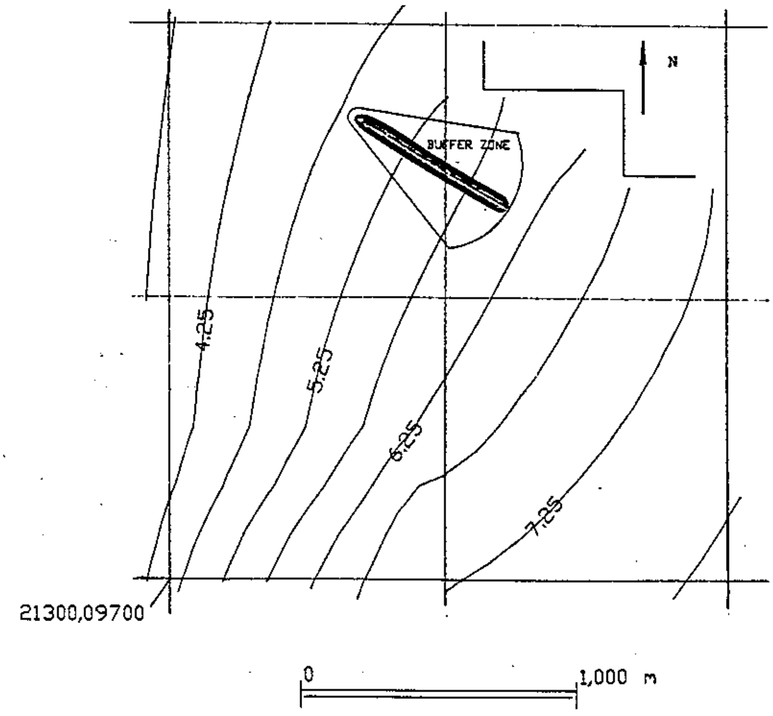

FIGURE 5 : 100 DAY TIME OF TRAVEL SPA FOR BALLYHANE BOREHOLE (227m^3/day) IN FISSURED LIMESTONE AQUIFER IN COUNTY WATERFORD. OUTPUT FROM FLOWPATH MODEL CONDITIONED BY KNOWLEDGE OF THE KARSTIC NATURE OF THE AQUIFER AND THE ADDITION OF A BUFFER ZONE TO ALLOW FOR UNCERTAINTY (after McDaid,1994)

PAPER TO INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP) SEMINAR

EPA LANDFILL MANUALS

Contents

Paper by J.G. Carty ME, BE, C.Eng., Eur., Ing, MIEI, MIWEM.

Manager,
Environmental Management
& Planning Division,
Environmental Protection Agency,
Ardcavan,
Wexford,
Ireland

Date: 25th April 1995

ABSTRACT

The Environmental Protection Agency (EPA) was established in July 1993 to licence, regulate and control activities for the purposes of environmental protection. The EPA is required to promote sustainable and environmentally sound development, have regard to the precautionary principle and the need for a high standard of environmental protection. It must also ensure as far as is practicable that a proper balance is maintained between the need to protect the environment and developments.

The Agency is required to specify and publish criteria and procedures for the selection, operation, management and termination of use of landfill sites for domestic and other wastes. Work commenced on two modules in mid 1994. These are Investigations for Landfills and Monitoring. Drafts were completed and circulated to an expert review panel and are currently being finalised. Two other modules will be prepared in 1995 on Site Selection and Operational Practices and I expect these to be published before the end of 1995. The overall approach of the EPA to the landfilling of wastes and the contents of the four modules commenced are outlined in this paper.

Key Words: Landfill Manuals, Investigations, Site Selection, Monitoring, Operational Practices.

1. INTRODUCTION

1.1 The Environmental Protection Agency Act, 1992 [1] was enacted on the 23rd April, 1992 and the Agency was formally established on the 26th July, 1993, to licence, regulate and control activities for the purposes of environmental protection.

1.2 The establishment of an independent national Agency represents a radical departure from previous systems of environmental control. The Agency will draw together research, control, monitoring and management practices in a unified and co-ordinated approach to protection of the environment and sustainable development.

1.3 The main functions of the Agency include:

- licensing and regulation of activities with significant pollution potential
- monitoring of the quality of the environment and the establishment of environmental databases
- the promotion of environmentally sound practices
- the preparation of National Monitoring Programmes
- the preparation of National Reports on drinking water, wastewater and landfills.

1.4 In carrying out its functions the Agency must operate in accordance with a set of principles set out in Section 52 of the Act. In particular, the Agency shall:

- keep itself informed of the **policies** and **objectives** of public authorities whose functions have, or may have a bearing on matters with which the Agency is concerned

- have regard to the need for a **high standard of environmental protection** and the need to promote **sustainable** and **environmentally sound** development, processes or operation

- have regard to the **precautionary principle** in relation to the potentially harmful effects of emissions

- have regard to the need to give effect, insofar as it is possible to the **"polluter pays"** principle

- ensure, insofar as is practicable, that a **proper balance** is achieved between the need to protect the environment (and the cost of such protection) and the need for infrastructure, economic and social progress and development.

1.5 The Agency considers that sustainable development requires the effective integration of economic and environmental considerations into the decision making process. This can be achieved in the context of waste management and disposal of waste to landfills through the following approaches:

POLLUTER PAYS PRINCIPLE:
The costs of monitoring a clean environment should be borne by those who directly or indirectly cause pollution.

PRECAUTIONARY PRINCIPLE:
If there are threats of serious or irreversible environmental damage lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation.

INTERGENERATIONAL EQUITY:
The present generation should ensure that the health, diversity and productivity of the environment is maintained or enhanced for the benefit of future generations.

ECONOMIC MECHANISMS:
Appropriate integration and use of economic mechanisms within decision making processes to achieve environmental protection at least cost to society.

The Agency fully subscribes to the waste hierarchy, namely that waste generation should be prevented if possible, reused or recycled, with landfilling then being one option for final disposal of the remainder.

1.6 Finalisation of the proposal for an EU Council directive on landfilling of waste [2] and enactment of the proposed Waste Bill [3] will result in major changes in the management, collection, recovery, and disposal of wastes. The Waste Bill will we understand include for the licensing of landfill sites by the Agency, specify the functions of local authorities in detail and provide a framework for the making of Regulations by the Minister for the planning, collection recovery and disposal of wastes. The role of the EPA in waste planning and regulation is likely to be expanded beyond that set out in the EPA Act 1992.

2. LANDFILL MANUALS

2.1 In the Environmental Protection Agency, Act 1992, it is stated that the Agency shall, as soon as possible, specify and publish criteria and procedures for the selection, management, operation and termination of use of landfill sites for the purposes of environmental protection. These criteria and procedures will be published in a number of modules under the general heading of LANDFILL MANUALS.

2.2 The current standard of operation of many landfills is unsatisfactory and significant improvements are required to achieve the standards proposed in EU directives and national legislation. A thorough, professional, consultative approach to site selection, operation, management and aftercare of our landfills will be required if we are to meet these standards. Our determination to deal with waste in a manner which is acceptable to the general public who are constantly demanding higher standards should be reflected in our approach to the planning, investigation, design, operation and management of waste recovery and disposal facilities.

2.3 With continued economic growth we are producing and consuming more goods and materials and we now produce one third more domestic and commercial waste than a decade ago. At present the majority of this waste is landfilled in unlined sites which many not meet current standards, and this practice cannot continue indefinitely.

2.4 In the Operational Programme for Environmental Services 1994/1999, published by the Department of the Environment, [4] Section 9 deals with Waste Management. In the subsections dealing with municipal waste the following paragraphs are included:

"The predominance of landfills as the method of municipal waste disposal in Ireland reflects the suitability of this system for areas of relatively low population density and with a dispersed settlement pattern. Landfill has also been seen to offer the most economical solution to waste disposal requirements. While there has been a trend towards larger, better engineered sites which cater for larger populations and lend themselves to improved operation and maintenance, many Irish landfill facilities will require considerable upgrading or phase out and replacement in order to meet the higher environmental standards demanded by prospective EU legislation and by public opinion generally.

While investment is needed to meet the anticipated requirements of the draft directive, this must be undertaken in a clearly focused and cost-effective manner, **taking full account of the EU and national policy emphasis on waste prevention, recovery and recycling".**

2.5 Under Section 62 of the EPA Act 1992, the Agency is required to specify and publish criteria and procedures for the selection, management, operation and termination of use of landfill sites for the disposal of **domestic** and **other wastes**. These criteria relate to:

- site selection
- design and bring into operation of sites
- impacts on the environment
- leachate management, treatment and control
- control and recovery of landfill gas
- operational guidelines, including classification of wastes and establishment of acceptance criteria for landfill
- acceptance of different classes of waste at different classes of sites
- fire, pest and litter control
- appropriate recovery, reuse and recycling facilities
- co-disposal of industrial and other wastes
- monitoring of leachate, other effluents and emissions
- termination of use and subsequent monitoring

2.6 Where criteria and procedures are specified by the EPA (under Section 62, EPA Act 1992) **the local authority responsible for the management and/or operation of a landfill site shall, where necessary, take steps as soon as is practicable to ensure that the management and operation of such landfill site complies with the specified criteria and procedures**. Where landfill sites are operated by other persons or organisations they will also be required to comply with these criteria and procedures.

2.7 The Agency is at present preparing manuals on:

- Site Selection
- Investigations for Landfills
- Monitoring of Landfills
- Operational Procedures

These manuals are being circulated to a representative review panel in draft form prior to publication. Members of the panel include representatives of the local authorities, the Department of the Environment, consultants, academic bodies, the City and County Engineers Association and the Environmental Health Officers Association.

3. SITE SELECTION

3.1 The selection of a site for a landfill is an interactive process. The developer of the site, the local authorities concerned and members of the public should all play a significant part in the selection process. The siting of landfills can lead to opposition and public protest. This is due, in part, to the use of unsuitable sites and the low standards of operation in the past.

Account should be taken of the three principles listed below:

- Proximity principle - waste should be treated or disposed of close to where it is generated

- Precautionary principle - potential risks at locations being considered should be taken into account in the selection process

- Polluter pays principle - costs of maintaining a clean environment should be borne by those who directly or indirectly cause pollution.

3.2 The selection of a suitable site for a landfill is an important mechanism for protecting the environment, public health and safety. Although engineered systems can be provided to offset some shortcomings, a site's natural attributes will greatly determine the risk of negative environmental impacts.

3.3 The factors used to evaluate a site's suitability start with the capability of the soil, geology and hydrogeology to provide protection from contamination. Issues such as land use can be used to exclude a specific site from consideration (e.g. proximity to a school, source of water supply). When comparing sites economic considerations can be used in the decision making process.

3.4 Innovative approaches are required which involve public participation and participation of elected members in order to ensure that site selection is based on acceptable criteria. At the earliest possible stage the public must be given the opportunity:

- to come to grips with the problem and the possible solutions to it

- to understand the approach being suggested

- to evaluate the potential impacts, both positive and negative

A merging of the scientific and sociological aspects of waste management must be considered if a successful outcome is to be achieved.

3.5 Local authorities are responsible for preparing Waste Management Plans. These plans should forecast future waste arisings and estimate the type and quantity of facilities that will be needed to deal with them. Waste management plans should also take account of the prevention, reduction, collection, recovery and disposal of waste within the functional area of the authority (and adjacent local authorities if a regional approach is adopted).

Two or more local authorities or a regional authority might consider making a joint Waste Management Plan. There are advantages to be gained from economies of scale, the broadening of options and in the case of landfill, the possibility of closure after a shorter period due to the larger waste volumes involved and the Agency recommends that a regional approach be adopted.

The Waste Management Plan should include a cost effective strategy for waste recovery and disposal having due regard to the safeguarding of the environment and the use of the waste as a resource. When landfill is likely to be the disposal route the plan should outline the site selection criteria against which possible landfill sites will be judged. The Waste Management Plan should quantify the amounts and types of waste which will require disposal and these figures are used to calculate the size of landfill required. The Waste Management Plan **should recognise that waste prevention and source reduction be given the highest priority** followed by waste recycling. Local authorities should take into account the needs identified in their disposal plans when considering plans for new facilities.

3.6 If landfill is to continue to be the principal method of waste disposal, the selection and ultimate use of a site is of primary importance. Existing sites must be evaluated and new landfill sites identified to provide sufficient capacity for long term needs and replace depleted or unsatisfactory sites.

3.7 The selection of the criteria can be critical to the successful conclusion of siting the facility. The criteria should be defensible, realistic and appropriate to the establishment of a landfill facility, should be based on sound technical data and on unbiased data evaluation. Once siting criteria have been agreed they should be ranked in order of importance before the site selection process commences. When a number of suitable sites are found using the siting criteria, a more detailed evaluation can be used to compare specific sites to one another. Criteria should include but not be limited to:

- avoidance of regionally important aquifiers
- protection afforded by subsoil
- impact on the landscape
- access
- existing land uses
- availability of cover material
- topography
- proximity to dwellings, surface waters
- proximity to source of waste generation
- status of the area

3.8 Proposals for the development of a landfill must take into account the requirements stated in the Planning Acts and Local Government (Planning and Development) Regulations [5]. The requirements stated in the County Development Plan and any Waste Management Plan or Strategy must also be considered. Under the European Communities (Environmental Impact Assessment) Regulations 1989-1994 [6] landfill sites with a capacity in excess of 25,000 tonnes/annum require preparation of an environmental impact statement, although an EIS may be requested for any landfill site. The Regulations provide for publication of notices advising that the statement is available and include provisions for the receipt of comments and consideration of the statement by the competent authority.

4. INVESTIGATIONS

4.1 The module on investigations is being prepared to assist developers in 'Site Characterisation'. That is to identify the pertinent characteristics of the areas and sites being considered and establish the information required to discriminate between potential sites in a logical, economical and transparent manner. Information generated in the investigations will be used in site selection, the preparation of preliminary and detailed designs, monitoring and aftercare plans for the site(s) chosen, the Environmental Impact Statement, submissions to the planning authority, the EPA and the Department of the Environment.

4.2 The purpose of an investigation is to determine the most suitable site or sites having regard to the objectives established in the Waste Management Plan or Strategy. At the conclusion of the investigations a recommendation in respect of one or more sites for use as a landfill should be made, if it is determined that a suitable site(s) exist. If at the conclusion of investigations at a particular site, it is determined that the site is unsuitable, then other potential sites should be investigated.

4.3 The information generated in the investigations outlined in the module will assist developers and operators to meet the requirements stated in the draft landfill directive. As the EPA will be proposed as the sole licensing authority under the Waste Bill the information requirements outlined will be taken into account by the EPA in licensing landfills. The conditions to be attached to licences issued to comply with national legislation and the Directive (when adopted) will be similar for public and private sector operations as with all other activities licensed by the EPA.

4.4 The investigations of potential sites should commence with a desk study in which areas considered 'generally suitable' are identified, rather than a site based approach where specific sites are chosen for further examination. In this way the risks associated with each area can be identified and areas where the risks are lower are chosen. The investigations should then proceed from preliminary assessment to detailed assessment. Investigations and site selection should always proceed in parallel to enable optimum use of the information generated.

4.5 The preliminary assessment stage will include a Desk Study, a Walk over Survey of the site, some preliminary investigation and some additional work such as use of geophysical techniques, trial pitting or shallow probing if required to reduce the number of sites being considered. At the preliminary assessment stage the initial list of areas and the sites should be reduced to a manageable number (say 3) on which a detailed assessment will be carried out. If there is sufficient time available baseline monitoring should be established at the short listed sites. At the conclusion of the preliminary assessment phase, a short list of sites on which further investigations could be completed should remain.

4.6 The objective of a detailed assessment is to establish comprehensive details of the topography, geology, subsoils, geotechnics, hydrology, hydrogeology, meterology, archaeology, ecology, landscape and land use at the short list sites. The extent of the investigations at each site and the number of sites which should be investigated is a matter for the judgement of the Principal Technical Adviser of the authority (in local authorities - the County or City Engineer) or company proposing the landfill. In our module on investigations, techniques suitable for use are listed and the general information requirements are listed. The results of the investigations should be presented in a report which identifies potential problems and outlines potential solutions. It should not be assumed that a site will be suitable for landfilling of waste because detailed investigations have been completed and the possibility of site rejection should remain until the alternatives have been investigated or eliminated for other reasons.

5. MONITORING

5.1 The monitoring undertaken at existing landfills is limited and the proposal for an EU directive requires that monitoring at stated frequencies be carried out at existing and new landfill sites as outlined below:

- Monitoring of all existing landfills at the following frequencies

Surface Water (minimum of two locations)	Quarterly
Groundwater (minimum of three locations)	Bi-annually
Leachate (at each discharge location)	Quarterly
Landfill Gas (each sector of landfill)	Monthly
Meteorological Conditions	Daily

- Typically 30 samples per annum per landfill will be required based on the above frequencies, excluding meteorological parameters which are monitored at the site or at an adjacent weather station.

- Closed sites must be monitored, generally at half the above frequencies.

5.2 We estimate that based on the estimated current number of landfills that between 3000 and 4000 samples will need to be taken annually by site operators for the 114 existing landfills. In addition the licensing authority (EPA) will in future take samples for compliance and verification and monitoring.

5.3 The results of monitoring carried out on an annual basis and a report on the operation and management of the landfills must be submitted to the EU Commission every three years. The EPA is required to prepare a national report on the operation and management of landfills under Section 62 of the EPA Act, 1992.

Source	Locations (minimum)	Frequency*	Samples per Annum	Typical Parameters
Surface Water	At not less than two points, one upstream and one downstream	Quarterly	8	pH, °C, EC, DO NH_4-N, Cl, COD
Groundwater	At not less than three points, one on inflow and two on outflow	Bi-annually	6	pH, EC, °C, DO, NH_4-N, CI, SO_4, ALK, TON, TOC, Na, K, Ca, Mg, Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn.
Leachate	At each discharge location	Quarterly	4	pH, °C, EC, NH_4-N, Cl, BOD, COD
Landfill Gas	Must be representative of each section of the landfill (assume one location)	Monthly	12	CH_4, CO_2, O_2, °C.
Totals			**30**	

* Longer intervals may be adopted if the data indicates that longer intervals are equally effective.

Table 1 LANDFILL AMENDED PROPOSAL Monitoring Requirements (Article 13 and Annex 111)

5.4 The collection and testing of samples must be undertaken by the operator of the site and the results transmitted to the competent authority (the EPA) for inclusion in the National Reports. The EPA proposes to adopt the same approach to compliance monitoring, auditing and the National Report as already adopted for the annual report on drinking water prepared by the EPA.

6. OPERATIONAL PRACTICES

6.1 If a landfill is to be operated without conflict with adjacent landowners and residents, the operator of the site must take account of legitimate concerns. If the landfill is operated efficiently and good management and operational practices are followed then landfills are likely to be accepted as an unwelcome but necessary facility. An Operating plan setting out how the site is to be operated should be prepared for each landfill site.

6.2 The factors which should be considered for inclusion in a documented Operating Plan for a landfill could include.

- Site Appearance
- Screening of Site
- Access and Security
- Landfill Designation
- Waste Categories Accepted
- Waste Screening

- Waste Acceptance Procedures
- Filling and Phasing of Developments
- Leachate Control
- Management of Nuisances
- Landfill Gas
- Litter Control
- Pest, Bird, Odour and Noise Control
- Formation and Stability
- Inspection and Maintenance
- Scavenging
- Safety
- Cover
- Site Operations and Responsibilities
- Monitoring

6.3 In the Operating Plan for the site, the means to be used to ensure that the site is operated to the required standards should be clearly set out and the chain of responsibility for control and management of the site detailed. Regular inspections should be undertaken and the outcome of the inspections documented.

7. LICENSING

7.1 The proposal for a directive on landfilling of waste sets out the general requirements for landfills. These include for containment, monitoring, management and aftercare of each landfill. The waste acceptance procedures and types of waste which may be landfilled are also listed together with the minimum permit (licence) requirements as outlined below. The permit contents and conditions must include particulars of the site, methods of pollution prevention and details of wastes being deposited. A financial security to ensure that the obligations set out in the permit are met must be provided. **Existing landfill sites, may continue in operation on the basis of an approved site conditioning plan** subject to the work being completed within ten years.

7.2 To comply with the provisions of the EU proposal for a landfill directive a conditioning plan will be required for many of the existing landfill sites or these sites will have to be replaced. Provision must be made for the monitoring outlined above and suitably qualified staff must be employed to operate the sites. **A national vocational qualification such as that being developed for water and sewage scheme operators** will be required as the management of the site must be in the control of a technically competent person. In addition professional and technical development and training of landfill operators and staff must be provided.

8. CONCLUSIONS

8.1 The standard of municipal waste landfilling operations will have to change radically if we are to meet the standards proposed in the proposal for an EU directive on the landfilling of waste. We must ensure that site selection, development and operation are completed to an acceptably high standard so that the environment is protected. The EPA recognises that:

- the best way to protect the environment is to consider all relevant factors; social, economic, technical, health, environment in an integrated approach

- waste prevention must become a priority for all waste generators.

- source separation is essential if the quantities of waste landfilled is to be reduced.

- a healthy environment is essential for economic development

- increasing effort is necessary to reduce the quantity of waste generated. This will include use of clean technologies, waste prevention, segregation at source and development of infrastructure for reuse and recycling.

- landfills are required to dispose of waste and it must be demonstrated that such sites are not causing or likely to cause ongoing environmental pollution

- landfill sites which are developed, conditioned, managed and operated in accordance with the EPA guidelines should meet the required standards.

- the cost of waste disposal will increase significantly as contained sites are developed and operated in accordance with the EPA guidelines.

- public confidence and trust in the ability of landfill owners/operators to manage the sites needs to be re-established.

8.2 Waste production has continued to increase in spite of increasing awareness of the environmental pollution potential of existing waste disposal outlets. We should all seek to reduce the waste we generate and adopt a responsible attitude which minimise the amount of waste that will require disposal. This will require progress on waste prevention, reuse and recycling if the targets proposed in the National Recycling Strategy [7] are too be met or exceeded.

8.3 Prevention, reuse, recycling, etc. will have to be addressed in a realistic manner. It is no longer sufficient to use 'the correct terminology' - progress in each of these areas is urgently required and provision of the necessary infrastructure should be an integral part of all waste management plans and strategies.

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THE ENGINEERING OF (A SUSTAINABLE) LANDFILL

Jonathan Derham, BSc, PhD, CGeol, MIWM, FGS. M C O'Sullivan & Co Ltd, Dublin

ABSTRACT

This paper suggests that sustainable landfill can and indeed must succeed. The sustainable landfill will have to be properly sited, planned and designed (and funded) to minimise, control, collect and dispose/treat the two principal long-term landfill emissions, namely landfill gas and leachate. In terms of the potential impact on groundwater the latter is the most significant. The current research area amongst waste management theorists 'The Bioreactor Landfill' and 'Accelerated Waste Decomposition' is endorsed. Engineering design criteria for the control and collection of leachate are discussed.

INTRODUCTION

Many people would find some difficulty in including landfill development within the sustainability concept. However, I believe one can have a sustainable landfill. Indeed we have to as landfill will in Ireland remain the dominant means of waste disposal for some time to come. Landfill is therefore an essential technology and if properly designed and operated is a good technology.

The development of a sustainable landfill starts with its conception as an element in a county or regional waste management strategy. Its siting in strategic terms must avoid 'regionally important aquifers' and other significant natural resources thus preserving these for future generations when surface water sources are depleted. Having sited and planned the landfill with a 'sustainable' approach, attention is then focused on design factors which have a bearing on long term protection of the environment.

What are those factors that potentially render landfill unsustainable? I would say they are principally the polluting and hazard risks to the environment, public health and enjoyment of amenity as a result of the production of:

- Landfill Gas (principally methane)
- Leachate.

The majority of the other pollution or nuisance factors associated with landfill are relatively short lived. For example dust or litter, where they occur, will usually only manifest themselves when the site is operational. Although not an emission, landfills do blight an area restricting some alternative uses of that land. This could be argued to be unsustainable, however I suggest that as the restored land can be used for agriculture or amenity then that argument is weakened.

Experience has shown that the principal two emissions of landfill will continue to be generated for at least three generations (and may be up to 7) (a generation would be considered to be approximately 30 years). Landfill gas will for the most part present itself at or near the surface of the facility (fully lined sites) where collection and treatment can be relatively easily put in place. Leachate on the other hand will largely present itself at the base of the facility and if not controlled and removed will ultimately impact on groundwater under the landfill. Retrofitting landfill gas control systems is technically straight forward however it is very difficult and expensive to retrofit a good leachate collection system.

The recent technological and regulatory movement to dry containment of landfill has had many benefits, however there is one significant disadvantage and that is that waste once capped is essentially mummified, thus significantly reducing degradation and stabilisation of the waste mass. Many of these modern facilities may now not stabilise for very long periods, if at all, thereby rendering this type of operational practice unsustainable. Stabilisation can be considered a state reached by the waste where leachate production/strength is reduced to acceptable levels/concentrations, landfill gas concentrations are within acceptable limits and further significant settlement of the waste mass is unlikely. The older 'dilute and disperse' facilities did stabilise more rapidly but pollution of the environment is an unpleasant side effect, for which we as the current generation are having to pay. Sustainability must therefore lie between these two technological extremes.

So what do we need to do to engineer a sustainable landfill? As mentioned above the principal long-term emissions of the modern landfill are leachate and landfill gas. This paper will concentrate on the achievement of sustainability with respect to leachate emissions as they are the most sifnificant with respect to groundwater. The solutions for landfill gas are technically similar and often connected with those for leachate. However I do not believe that landfill gas represents the same pollution risk as leachate because of the case of retrofitting control systems. The sustainable landfill must attempt to achieve if possible a number of objectives with respect to leachate emissions:

- Minimisation
- Control
- Collection
- Disposal

There is also the matter of funding of aftercare. The subject of bonds etc. is not discussed here as I will limit my paper to aspects of 'technical' sustainability. However suffice as to say funding of future aftercare requirements are an essential element of the sustainability argument.

MINIMISATION

The problem with the currently recommended 'dry tomb' landfills is that though annual gas and leachate production is minimised, the site may not stabilise for many years. Annual emission quantities may therefore be small, however the cumulative production over such a lifespan will not achieve minimisation to satisfy the sustainability argument. I believe that in order to achieve sustainability minimisation must be argued to be the reduction of emissions to the shortest possible period. This may be accomplished in a rapidly stabilised landfill by a technique know as Accelerated Waste Decomposition (Harris et al, 1994). The technical literature are calling landfills employing this technique 'Reactor Landfills', an unfortunate title as outside the industry this label may evoke associations with a technology we would wish to distance ourselves from. A number of years ago the term Bioreactor was coined by those involved in the landfill gas industry. I would wish the Bio prefix remain as it is, to my mind, both an apt and far less emotive word. This may seem a small point but given the highly public nature of the waste industry and the national sensitivity to same, we should avoid unnecessary technological associations with a less than perfect industry.

It is suggested then that the sustainable landfill must employ Accelerated Waste Decomposition (AWD) in order to achieve stabilisation or 'final storage quality' within a generation. AWD is achieved by flushing the wastes with water. Recirculation of leachate has been suggested as a means of achieving this. You may be familiar with the term 'below cap irrigation'. There is ongoing research into the likely irrigation rates necessary in order to achieve final storage quality. Knox (1990) suggests that between five and seven 'Bed Volumes' of water (a Bed Volume is the total moisture content of the landfill including absorbed water and free leachate) will have to pass through the waste in order to achieve satisfactory reduction in, for example, ammonia concentrations.

Recirculating the leachate produced by the site is unlikely in itself to provide enough moisture to achieve the most efficient accelerated degradation. Indeed given the high quality of modern landfill cap design where water infiltration is virtually nil, then leachate production will be dramatically reduced once the cap is in place. Without the large contribution of rainwater infiltration the quantities of leachate presenting itself at the base of the facility will reduce over time. One of the reasons being;

$$C_nH_aO_b + [n - (a/4 + b/2)]\ H_2O \rightarrow \quad (n/2 - a/8 + b/4)\ CO_2 + (n/2 + a/8 - b/4)\ CH_4$$

This may be simply expressed as: Cellulose + Water => Carbon Dioxide + Methane

The anaerobic fermentation of carbohydrates (cellulose) to produce Methane and Carbon Dioxide will consume water. For cellulose, $C_6H_{10}0_5$, the above equation indicates that 18g (1 Mole) of water are consumed for every 72g (6 Mole) of carbon fermented. Taking a realistic yield of landfill gas from refuse of say 200m^3 gas/t, the degradable carbon content of the refuse would be;

$$[(200 \times 1000) \div 22.4] \times 0.012 = 107\text{kg/t}$$

Thus water consumption per tonne of waste = $(107 \times 18) \div 72 = 27$ l/t

The 200m^3 gas/t is a 'lifetime' gas production value (conservative). If one assumes an annual yield of say 10m^3 gas/t.a, the water consumption rate would be 1.34 l/t.a. Thus a gassing landfill containing 1 Mt of refuse might consume 1,300m^3 of water per annum. Where active gas extraction is in place, up to 500m^3/a of moisture (in a landfill with 1 Mt refuse with gas production of 10m^3/t.a) may be removed from the system via the naturally saturated gas vapours (Knox, 1990). It is possible therefore to consume up to 1800m^3/a of leachate in a closed landfill. However one must consider that the typical natural moisture content range of domestic refuse is 250 - 400 l/t (UK DOE, 1991). Using the example given above of a 1Mt facility, this would yield a natural moisture content of 300,000m^3 (taking 300 l/t as average and assuming it was all available) Added to this is the amount of water taken up by the waste mass during filling and prior to covering, i.e. the absorptive capacity of the refuse. Municipal refuse would have a primary absorptive capacity typically ranging 100 to 150 l/t. In our above example, this would represent approximately 130,000m^3 of liquid taken in by the landfill before leachate is produced. That added to a typical natural moisture content for domestic waste given in the example given above (300,000m^3) yields a potential 'moisture bank' of 430,000m^3 in this 1Mt facility. This facility if capped and no additional water supplied would consume moisture at a rate of 1800m^3/a (see above) principally in the production of landfill gas. At this date it would take the facility some 239 years to dry out (gas production ceases).

What all this means is that the post-capping irrigation process will, in order to reduce stabilisation to one generation, have to add water to the system in addition to that held within and produced by the waste mass. There is much work yet to be done in this area in order to demonstrate that the theory of Accelerated Waste Decomposition (AWD) can work both in terms of the engineering and scientific requirements and specifications. I believe it is the way forward. I do however have some reservations, the principal one being all to do with the plastic bag! Most households pre-wrap their waste in plastic bags. If these bags are not broken by the collection and disposal processes the waste contained within will not be readily available to the AWD process. Disturbance may rupture all the miniature 'Dry Tombs' and plastic bags and make available the leachate forming material contained within. I suspect that a significant percentage of modern facilities will suffer this problem despite the mechanically aggressive nature of collection and compaction plant. One outcome of current research into AWD may be that in order for the process to have the best chance of success then all incoming biodegradable waste must be shredded prior to burial (Pre-treatment).

CONTROL

The next important feature of the 'sustainable landfill' is the engineering of leachate and gas control. Basically this is what we commonly refer to as the lining or containment of a facility. I will not reintroduce all the various lining system options (double and single liners, double composite etc.). Only one of these containment principles has gained universal approval for modern MSW landfills and that is the composite liner (Figure 1) comprising a natural or processed mineral layer with a permeability of 1×10^{-9} m/s or less, in intimate contact with a high density polyethylene (HDPE) flexible membrane liner. This system is an excellent marriage of the robust, self healing and attenuating properties of a mineral layer with the chemically robust and low permeability characteristics of a synthetic liner. It is the recommended containment design principle in Germany, Denmark, UK and the US.

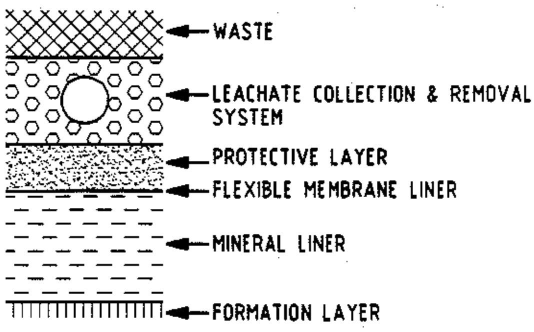


Figure 1: The Composite Basal Liner

The addition of an FML to the lining equation has significantly improved on the predicted leakage values for MSW sites even when the FML has a number of holes (Table 1). One advantage the reworking of the mineral layer to achieve the containment criteria of 1×10^{-9} m/s for a 1m thick layer, has over the reliance on in-situ natural mineral liners that is one achieves a consistency of quality in the seal. If a bentonite enhanced soil (BES) liner is used, it is technically straightforward to achieve permeabilities (k) of 1×10^{-10} m/s or lower. In these cases, I would argue that a 1m thick layer would not be required as a BES layer 300mm thick has a leakage rate which is approximately five times lower than a 1m layer with a k of 1×10^{-9} m/s (Table 1). Indeed a mineral layer with a $k = 1 \times 10^{-10}$ m/s which is only 5mm thick has an equivalent leakage rate to that of a 1m thick mineral liner with a permeability of 1×10^{-9} m/s. I would suggest though that to engineer a mineral layer as important as a landfill liner for thicknesses < 100mm would present some technical and confidence difficulties.

There is the option of using a geosynthetic clay liner (GCL) under the FML (some of which can achieve k values of 1×10^{-12}). I feel that this material is under-valued as a containment engineering method.

TABLE 1: Comparative Leakage Rates

Liner Systems	No. of holes in FML	Area of Hole	Permeability of Soil	Head of Leakage	Leakage m^3/ha/yr
Composite[1]	5/ha	$100mm^2$	1×10^{-9}m/s	1m	0.68[2]
Composite[1]	25/ha	$100mm^2$	1×10^{-9}m/s	1m	0.79[2]
5m of Clay/BES	-	-	1×10^{-9}m/s	1m	378[3]
1m of Clay/BES	-	-	1×10^{-9}m/s	1m	631[3]
300mm of Clay/BES	-	-	1×10^{-10}m/s	1m	137[3]
5mm of Clay/BES	-	-	1×10^{-10}m/s	1m	632[3]

Notes: (1) 1m of mineral liner @ 1×10^{-9} m/s, and a 2mm HDPE FML, (2) Good contact, based on Giroud et al (1989), (3) Darcy's Law Q = Kia.

The liner materials are only a small part of the lining 'system' comprising the following:

- Formation layer
- Mineral liner
- F.M.L.
- Protective layer
- Drainage layer or leachate collection and removal system (LCRS)

The liner's primary function is to provide a hydraulic contrast sufficient enough to discourage downward migration and encourage leachate flow in the LCRS. The liner's secondary function - which should only be considered an emergency function - is to impede and attenuate leachate leakage.

Table 2 below presents some examples of leakage rates for liners under various heads. What this table clearly demonstrates is that the critical factor in determining leakage rates in composite lined facilities is leachate head and not the number of holes in the FML. For example a threefold increase in leachate head from 1 to 3m results in an 150% increase in leakage ($k=1x10^{-9}$ m/s), whereas a five fold increase in the number of holes (5 to 25) results in a 16% increase in leakage (1/m head and $k = 1 \times 10^{-9}$ m/s). It follows then the single most important element in a lining system is that part which permits control of leachate head, i.e. the leachate collection and removal system (LCRS). Designers and regulatory bodies must include detailed consideration of this element of the system.

TABLE 2: Annual Leakage Rates for a Composite Liner (m^3/ha/yr)

			HEAD OF LEACHATE				
Permeability of Soil Component	**No. of FML Holes/ha**	**Soil Liner Thickness**	**250mm**	**500mm**	**1000mm**	**3000mm**	**5000mm**
$ks = 1 \times 10^{-9}$ m/s	5	1m	0.19	0.52	0.68	1.82	2.88
	25	1m	0.22	0.43	0.79	2.14	3.39
$ks = 1 \times 10^{-10}$ m/s	5	1m	0.04	0.07	0.012	0.33	0.53
	25	1m	0.04	0.08	0.14	0.39	0.62

1. Based on Giroud et al, (1989) [$Q = 0.21hw^{0.9}\ a^{0.1}\ ks^{0.74}$]. Area of each hole $100mm^2$. Good Contact.

A containment system will extend up the sides of the facility, though need not necessarily be composite as the risk is not the same because, with a good internal drainage system, leachate will not form a 'head' on the sides of a facility. Side containment is principally required to provide a hydraulic contrast and prevent uncontrolled lateral gas migration. In most modern facilities, the base and side wall containment will be linked to the capping system thereby ensuring total containment and thus assisting total control of the two principal long term emissions.

The capping layer will more than likely have a sub-cap gas collection layer. This layer is less critical than the LCRS as gas by its nature is less polluting and also it essentially presents itself at the sides and roof of a facility where it can easily be collected. A LCRS on the other hand requires careful design and construction. Collection systems form the third element of the four landfill sustainability criteria' mentioned in the introduction to this paper.

COLLECTION

The leachate collection and removal system (LCRS) has to be considered the keystone element of a lining system. A LCRS generally takes the form of a granular drainage layer containing pipework (Figure 2). French drains or herringbone based systems would no longer be considered adequate. A full drainage blanket extending up the sides of the facility (prevents perching) is now the recommended norm in the UK and Germany.

There are synthetic drainage systems available, however they are not cost effective where a supply of natural material is available. They also provide some technical difficulties when considering maintenance of the LCRS, particularly when used on the base of the site.

There are six principal features every LCRS must demonstrate:

- Chemical Robustness
- Physical Robustness
- Fines Free
- Permeability $\geq 1 \times 10^{-2}$ m/s
- Maintainability
- Monitorability

Leachate is an acidic liquor, therefore it is not prudent to use, for example crushed limestone or sandstone with a calcareous cement as the drainage medium. The material must be capable of withstanding the loads resulting from burial under 10-30m of waste. Many LCRS designers have placed geotextile filters between the LCRS and the waste so as to prevent clogging of the systems with fines. What tends to happen in this case is the geotextile itself clogs thereby preventing removal of the leachate. I would be against the use of filter systems above a LCRS. Provided the granular layer is not too fine ($k \geq 1 \times 10^{-2}$m/s), the slope of the cell > 2% and the leachate is actively extracted (i.e. a dynamic system) biological or sediment fouling should not be a major concern. Studies by Koerner and Koerner (1990) concluded that clogging was a serious concern in MSW facilities where filter systems were used. It may be argued that if the filter systems clogs, then there will be no leachate head on the liner, thus no leakage. This is true, however it will not help the Accelerated Waste Decomposition case. Furthermore, this condition may introduce stability problems especially for above ground landfills.

The spacing, dimension and slot size of the pipe system in the LCRS is determined by, inter-alia, the head (max), slope, infiltration intensity, k of drainage layer, flow velocity and roughness. Well established hydraulic equations developed by Moore (1993), Gupta (1989), Fox and McDonald (1995) and many well known text books are available to assist design. The strength of the pipe should also be considered as it will have to survive burial under 10-30m of waste. Another consideration would be the chemical stability of the pipe material. It is recommended that HDPE is used as it is the most chemically resistant of all available materials. Many modern facilities use pipe work with corrugated external walls. This has the advantage of cost effectively enhancing the strength of the pipe, however the external ridges do provide a locus for sedimentation as the unslotted intra-ridge hollows will be somewhat protected from the fast flow conditions encouraged in the mineral layer. Furthermore the ridges may also slow the inward movement of water to the slots (located in the intra-ridge area) sufficiently to cause sedimentation. I would wish that the HDPE pipework used in LCRS's would be smooth walled with large open slots (>5mm). This would assist the maintenance of rapid flow in the LCRS thereby inhibiting sediment and biological clogging.

Another very important factor for a LCRS is that it should be maintainable. This is achieved by inclusion of rodding ports in the design of the system (Figures 2 and 3). The pipework where possible should be brought up to the sides of the facility to the surface where access is provided. The main access will be through the leachate sump access pipe. Modern facilities should move away from

SECTION THROUGH LEACHATE COLLECTION & REMOVAL SYSTEM

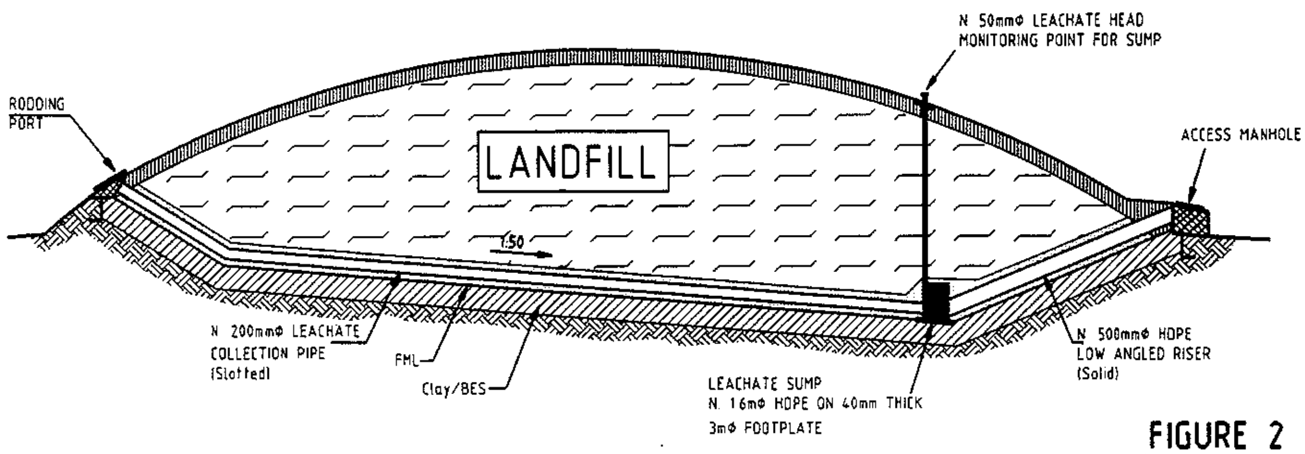
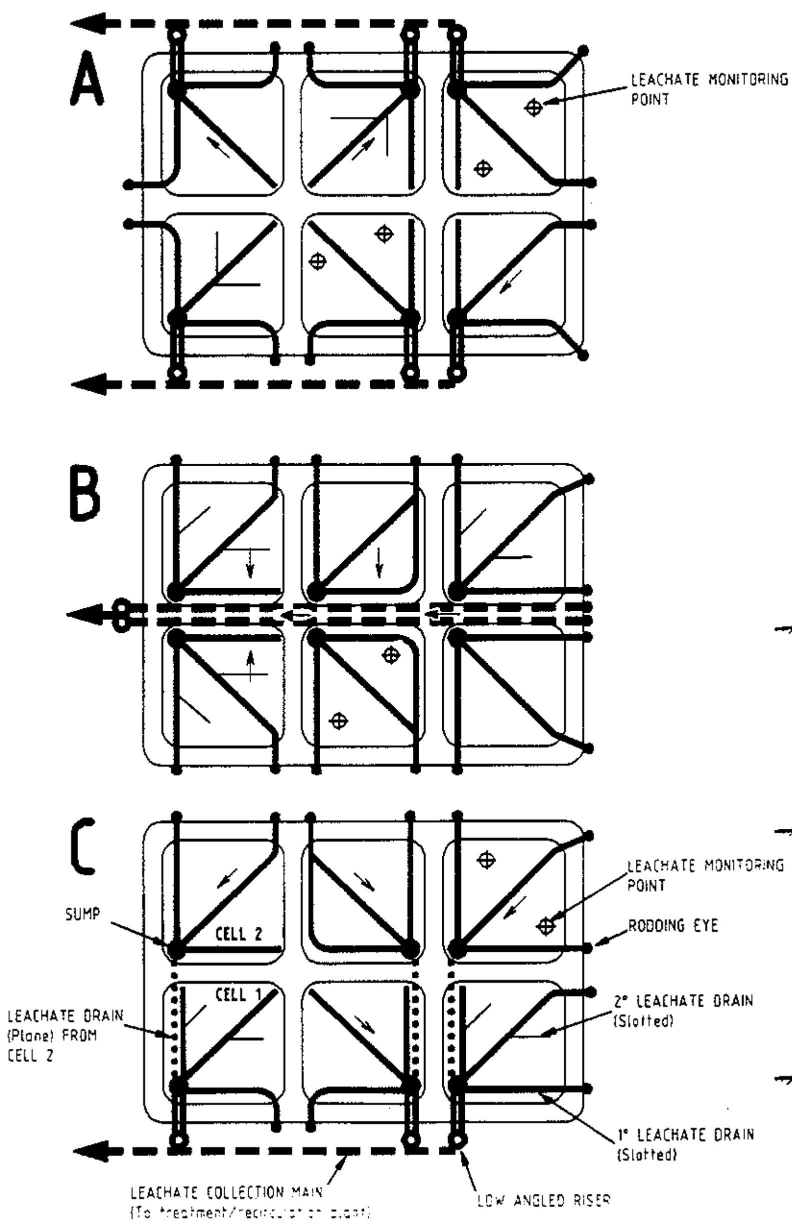
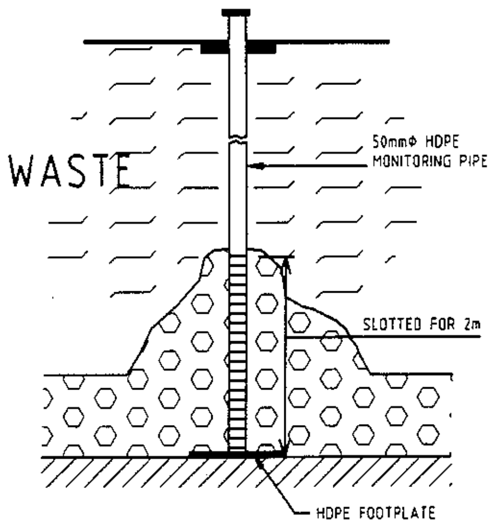


FIGURE 2

EXAMPLES OF LCRS CONFIGURATIONS





LEACHATE HEAD MONITORING PIPE

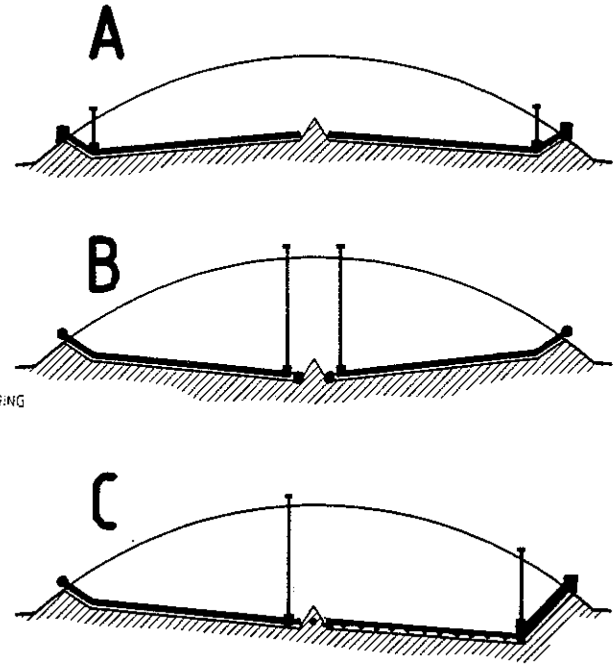


FIGURE 3

large vertical leachate chimneys as they require special and detailed design and construction to prevent damage to liner systems. They also hinder landfilling operations, are relatively hard to get leachate from, and are prone to collapse or significant movement. The current trend towards above ground landfills suits the abandonment of vertical chimneys and their replacement by 'low angled risers' which are structurally and operationally a superior option (Figures 2 and 3).

By careful design of the LCRS pipework systems, one can achieve a layout that maximises access to the pipework, at least to the primary collectors. Where a facility has multiple cells, it is operationally desirable to be able to control the leachate in each cell independently of one another. Figure 3 gives examples on how this might be achieved.

The last and most important feature of a successful LCRS is that it can be monitored. The operator has to be aware that leachate head is being successfully controlled. This can be achieved by the inclusion of low technology leachate monitoring pipes in the cell as it is constructed (Figure 3). At least three such points should be included per cell (triangulation).

DISPOSAL

The final criteria necessary for the sustainable landfill is to design for disposal of leachate within the concept of sustainability. Recirculation of leachate will assist in minimising that requiring treatment and disposal. The whole area of treatment of leachate is quite specialised. One point I would wish to make is that the future landfill will have to carry out a significant amount of pre-treatment of its leachate on site prior to licensed disposal to either sewer or surface water system. All future facilities will have a mini waste water treatment facility located on site which will introduce another element of expertise required in site management terms.

SUMMARY AND CONCLUSIONS

This sustainable landfill will have to be sited, planned, designed (and funded) to minimise, control, collect and dispose of its principal two emissions landfill, gas and leachate, within one generation (30 years). Dry tomb landfilling is unsustainable and should be superseded by the technically superior Bioreactor Landfill where Accelerated Waste Decomposition is practiced. The modern facility will be composite lined throughout its base and will have a superior leachate collection and removal systems installed which would both control leachate head and facilitate recirculation. Leachate head is the principal driving force for leakage. Accelerated Waste Decomposition will require liquid input in addition to that resulting from precipitation. A below cap irrigation system will be required in order to facilitate recirculation of leachate and will require very careful design (structurally not too dissimilar to a basal containment system).

It may be desirable to avoid capping the waste for as long as possible so as to encourage rain infiltration thereby providing the additional moisture requirements. This could result in the construction of temporary restoration layers (to prevent litter and enhance visual appearance) during the stabilisation period. The irrigation system would still be installed in the top layer of waste. This type of approach may hinder gas extraction/utilisation as it may encourage draw-in of fresh air. It will allow gas to ventilate freely to the atmosphere. It might also present difficulties in controlling the irrigation rates. There is likely to be public opposition to any prolonging of the full restoration phase. I therefore feel that technically the way forward is a below cap system with the cap installed progressively and following cell completion.

The modern facility will have to possess sophisticated leachate management (storage, pumping, monitoring and treatment) facilities. Even if the Bioreactor technology fails the landfill will still be required to control, collect and dispose (treat) its emissions, thus all the technical considerations discussed above will be required. I believe there is scope for AWD to work in Irish MSW sites where industrial and hazardous wastes are not accepted. It is likely that some form of waste pretreatment (shredding) will be required if AWD is to be truly successful.

There is one thing our future generations will not thank us for and that is pollution of their groundwater. They will probably find the financial resources to continue and enhance the future management of our closed landfills, but they may not so easily find ready supplies of uncontaminated groundwater. We therefore have a primary duty to design to contain and control leachate emissions to the highest possible standard. To achieve stabilisation within one generation would be great but this is secondary and its achievement must not compromise the primary objective of protecting the existing environment.

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LANDFILL STUDIES: THE ROLE OF THE HYDROGEOLOGIST

Suzanne O'Sullivan
Hydrogeologist

ABSTRACT

As environmental awareness of the potential hazards of landfilling has grown, the associated science of hydrogeology has also evolved. Groundwater, not long ago considered of little or no concern because it was largely unseen, became the focal point of scientific investigations on potential landfill sites. Technology has now developed to the extent that the natural hydrogeological characteristics of a proposed site are often seen as no more than the basis for an elaborate engineering plan, and it has often been stated that "any site can be engineered". This paper seeks to show the importance of site hydrogeology, how it is compatible with, rather than subservient to engineering, and the contribution made by the hydrogeologist to the planning procedure.

INTRODUCTION

Landfilling has developed from being a necessary evil to rid us of our ever increasing wastes, and has now become almost a science in its own right. At one time, the merits of a potential site were a location close to the source of waste production, and a pre-excavated hole which could be infilled to restore the status quo. As environmental awareness has grown, and in particular, awareness of groundwater as a natural resource, sites for landfilling have been scrutinised more and more carefully before being deemed acceptable.

The potential for surface and groundwater pollution has probably been seen as one of the greatest causes for concern, and prior to more stringent regulations in recent years, landfill site investigations predominantly consisted of a baseline hydrogeological study. The concept of "dilute and disperse", whereby contaminants emanating from a landfill are assimilated and diluted by the receiving waters, was widely accepted, and the need for leachate control and treatment was considered unnecessary except in extreme circumstances, which could probably be avoided.

Gradually, the practice of landfill engineering has grown to the extent that all landfills in the country are now being engineered to some degree, and each potential landfill site is the subject of a major environmental impact assessment. Many would now believe that the engineering aspects of landfill site development are the most important elements, and that the baseline studies carried out serve only to define the nature and extent of the engineering measures required. It is not uncommon to hear the claim that "any site can be engineered for landfilling".

I believe that the hydrogeological characteristics of a site are fundamental in site assessment, and that engineering should be used to enhance natural characteristics, rather than purely overcoming faults and defects. There is, of course, a role for engineering in artificially altering site characteristics. However, the extent of alteration should be weighed up against the public need for the development, and the lack of any other suitable site.

The nature of the climate and geology of Ireland dictates that water will always play a very important role in landfilling in this country. Below, I am going to discuss what hydrogeological aspects should be addressed when considering a site for landfilling, and what the long-term implications of baseline studies may be.

ENVIRONMENTAL IMPACT ASSESSMENT

It is safe to say that all municipal landfill sites in Ireland will be the subject of an environmental impact assessment in the future. The EIA comprises three units with respect to hydrogeology:

1. A Baseline Study
2. Prediction of Impacts
3. Recommendations for Amelioration

The Environmental Protection Agency have published guidelines on carrying out EIA's, and I do not propose to go through these in detail. Below is a summary of the major points which should be considered.

BASELINE STUDY

The function of the baseline study is to adequately describe the hydrogeology of the site. so that a decision on site suitability can be made. The following aspects need to be considered:

Aquifers:- is the site underlain by one or more aquifers, and what is their importance? Are they of major regional importance or of local benefit? Are aquifers used for groundwater abstraction now, or is there potential for use in the future?

Vulnerability:-how easy is it for contamination to enter groundwater, and move throughout an aquifer? Is the groundwater table close to the surface, or are aquifers protected by low permeability strata? Is bedrock fissured, allowing rapid migration of contaminants? Do swallow-holes provide natural conduits for surface contamination to reach groundwater?

Groundwater Movement:- what direction does groundwater move in beneath the site, and is the direction similar in bedrock and overburden? Is movement rapid or slow?

Surface Waters:- are there any surface waters flowing through or around the site? Are they of aesthetic or ecological importance in their own right, or do they feed larger more important waterways?

Baseline Hydrochemistry:- what is the natural chemistry of the water, including seasonal variations? Is it potable, or even pristine?

These are, broadly, the categories which need to be addressed. The detail of investigation required will depend on the individual characteristics of the site, and the scope of work may change, as the investigation continues.

PREDICTION OF IMPACTS

This section of the EIS will describe what environmental impacts may occur if landfilling commences. These impacts will include those if no remediation measures are taken, and also those which are likely to occur if remediation measures fail. The impact of the remediation measures themselves should also be considered. For example, what would happen if surface water channels are diverted, or saturated material removed from the base of the site.

Negative impacts are most often highlighted in EIS's, but it is important to identify positive impacts also. For, instance, deepening of a channel to prevent flooding of a landfill site might also benefit adjacent areas.

RECOMMENDATIONS FOR AMELIORATION

The hydrogeologist may consider proposed remediation measures inadequate, based on the results of the hydrogeological investigation, and recommend that further steps be taken. In some cases, it may be considered that even extensive engineering measures are inadequate to sufficiently reduce the risk of environmental degradation.

METHODOLOGY

It is not too long since a landfill site investigation consisted of drilling and logging the bare minimum of three boreholes, levelling them in, and taking a water level measurement and water sample at each one. This procedure might seem somewhat basic to us now, but it was a very important step in acknowledging the importance and vulnerability of groundwater, and recognising the need to have an understanding of the hydrogeology of a proposed landfill site.

Recent Environmental Impact Assessments of proposed landfill sites have been much more detailed in keeping with the trend towards larger, designed, engineered and managed sites. In some cases, the intensity of the investigation has been partly driven by third-party objections, which has led to scrutiny of every minuscule detail.

SUB-SURFACE INVESTIGATIONS

These will take the form of trial pits and boreholes, and, in some cases, geophysics. Each has it's role to play in the hydrogeological investigation.

There is a tendency to concentrate on protecting bedrock, but the overburden itself may also constitute an aquifer. Near-surface aquifers are often discounted as major sources of water, because of their vulnerability to contamination. However, they are important aquifers, especially in localised areas.

Water-table aquifers are generally in hydraulic continuity with surface water bodies, and are a medium by which contamination may be transported into rivers, lakes or canals. An understanding of the behaviour of groundwater in water-table aquifers is fundamental in any landfill site investigation.

Trial Pits
Trial pits are an inexpensive means of assessing the top few metres of overburden, allowing sub-surface access for examination of strata and sampling of material. They are rarely good for taking water levels, and care should be taken when sampling water from trial pits.

Borehole Drilling
Boreholes provide the means of penetrating and logging deeper strata, and may subsequently be constructed to allow ongoing monitoring of groundwater levels and quality.

One question which is often asked is how many boreholes are sufficient for a hydrogeological investigation. The answer, unfortunately, is that there is no definitive answer. Generally speaking, the more heterogeneous the geology, the greater the number of boreholes that will be required to adequately characterise the site. It is difficult to define areas of fissured bedrock, as even a large number of evenly-spaced boreholes may not sufficiently describe the fissure pattern. Often five or six boreholes would be considered adequate, but at one site, almost forty boreholes were drilled during the course of investigations. In this particular case, the more information that became available from different boreholes, the more complex the geology appeared.

What is most important is to ensure that the boreholes are properly constructed, and that the data derived from them is correctly interpreted. It is essential that boreholes be constructed into either bedrock or overburden, and that water levels or water samples taken from individual boreholes are wholly representative of one or the other.

Composite water levels, i.e. those obtained in boreholes which penetrate both bedrock and overburden, may be misleading. The direction of groundwater flow in water-table aquifers is largely controlled by topography, while flow in deeper, bedrock aquifers is more likely to be influenced by geological structure. The interaction between overburden and bedrock is a critical element in the hydrogeological investigation, and is fundamental in understanding the fate of contaminants within the hydrogeological system.

GROUNDWATER FLOW

Groundwater contour maps generally show groundwater flowing in straight lines. In reality, this is rarely the case, as flowing water, be it on the surface, or below ground, will always tend to take the path of least resistance. Geological heterogeneities cause groundwater to flow preferentially through more permeable strata, or lenses within strata. This may mean that groundwater velocity through, for example, the centre of a gravel esker, may be significantly greater than that calculated through the entire gravel aquifer.

Similarly, low permeability strata may provide good natural protection for an underlying aquifer. However, lenses of sands and gravels can allow relatively quick vertical flow of groundwater where they occur, and this, of course, greatly increases the potential for downward migration of contaminants.

In Ireland, bedrock and overburden geology show considerable lateral variations, and heterogeneities occur within individual strata. It is possible, therefore that relatively complex groundwater flow mechanisms may operate within a site of 50 to 100 acres.

A site investigated a few years was located in a gravel esker. After a number of years in operation, domestic boreholes downgradient of the site became contaminated. Some located relatively close to the landfill did not experience contamination. This is because these boreholes were not exploiting groundwater from the core of the esker, where contamination was rapidly transmitted. The time taken for contamination to reach the furthest borehole was far less than would be expected on the basis of a pumping test carried out on another borehole closer to the landfill. The second borehole was located in gravels also, but they were not the esker core gravels, and the borehole was not directly downgradient of the landfill.

This illustrates how different parts of the same aquifer may behave very differently, and that superficial judgements on potential contaminant movement may be misleading.

INTERPRETATION OF RESULTS

Ten years ago, I undertook research on groundwater quality in the vicinity of six landfill sites in Leinster. Five of these sites were uncontained, and located in disused rock quarries and gravel pits, as would have been very common even then. The results suggested that contamination of domestic boreholes adjacent to two of the sites was directly related to the operation of the landfill site. However, in the other three cases, there was no detectable contamination of groundwater from each of the landfill sites investigated.

The objective of the research was to investigate the effects on groundwater of a number of individual landfill sites. These sites were chosen on the basis of a sufficient number of sampling points, i.e. domestic boreholes or springs, being available in the vicinity of the landfill. An attempt was made, within financial and temporal constraints, to establish if there was any pattern to be observed amongst landfill sites in similar geological settings. No pattern was observed, and this may be attributed in part, at least, to the small number of sites under investigation. However, what was very evident was that each site was hydrogeologically unique. No contamination was observed where it might reasonably be expected, and vice versa. Much more detailed investigations, beyond the scope of the project, would have been necessary to establish the hydrogeological regime at each site. The same criterion may be applied to potential sites. Each one is individual and must be treated as such. No assumptions about suitability should be made on face value, or superficial results.

CONTRA-INDICATIONS

Even though each site is individual and unique, there are some characteristics which render the suitability of a site doubtful. These are:

- High or surface water table
- Fissured or broken bedrock
- Close proximity to surface or groundwater abstractions
- High permeability deposits e.g. gravels
- Marked heterogeneity in geological deposits

This is not an exhaustive list of contra-indications, but represents the most common natural defects in landfill sites. The existence of any one of these factors does not necessarily rule out the use of a particular site. However, they are characteristics which are undesirable, and the more of them that occur together at any one site, the more likely that site is to be hydrogeologically unfavourable.

HYDROGEOLOGY, ENGINEERING AND PLANNING

PLANNING A LANDFILL

The hydrogeologist may get involved at various stages when a new landfill site is required. The first option is to carry out a study on a regional scale, to identify the most suitable geological situations for landfilling. Secondly, a comparative study may be undertaken on a number of pre-designated sites. In this case, the hydrogeologist can identify which site is most suitable, and how the sites compare with each other. This will be an important aid to the planner in weighing up the hydrogeological suitability against other site characteristics. Finally, the hydrogeological study may be part of an Environmental Impact Assessment on one specific site. In this situation, the hydrogeologist will be making site-specific recommendations.

THE INDIVIDUAL ROLES

There is a theory that any natural shortcomings of a proposed landfill site can be overcome by engineering, and that, all other things being equal, any site can be used for landfilling. In keeping with this theory, the hydrogeological baseline study would have no contribution towards the final planning decision as to whether or not a site should be accepted or rejected as suitable. Its function would be purely to determine the extent and nature of the engineering measures required. This is, of course, a very important function, but it should not be the only one.

The hydrogeologist can recommend whether or not the inherent natural characteristics of a site render it suitable for landfilling. He or she can identify the potential risks involved, and what the magnitude of these risks is. In some cases, engineering measures may be sufficient to eliminate the risks, or reduce them to an acceptable level. There may be situations where the hydrogeologist feels that the risks are too great, regardless of the ameliorative measures taken.

The recommendations of the hydrogeologist are made purely on scientific fact, although individuals may vary in their interpretation of risk levels. The engineer must look at all negative environmental impacts, hydrogeological or otherwise, and come up with a design which will minimise those impacts. The engineer must also deal with financial issues. In general, the less suitable a site, the more expensive it will be to construct and operate.

The role of the planner is to take the hydrogeologist's results and recommendations, and weigh those up against the public need for the landfill. The hydrogeological aspects must, of course, be taken in context with other environmental and social aspects, and the planner must consider the merits and shortcomings of a site from all points, and make a decision as to which aspects are of overriding importance.

TRACE ORGANICS IN IRISH GROUNDWATERS

by Shane Bennet, Hydrogeologist, K.T. Cullen & Co. Ltd.

1. ABSTRACT

"Trace Organics in Irish Groundwaters" was the title of a STRIDE (Science and Technology for Regional Innovation and Development in Europe) Environment Sub-Programme undertaken between 1992 and 1994. A comprehensive report was submitted to the Department of the Environment in November 1994.

Two geographical areas were chosen:

- *The twenty six counties area were selected for a nationwide investigation of groundwaters historically-associated with trace organic contamination. Groundwater was sampled at sixty (60) locations which were spatially distributed throughout the twenty six counties.*
- *The Mid Kildare or Curragh Aquifer was chosen for a regional investigation of trace organics in a recognised major aquifer. Groundwater was sampled at thirty one (31) locations spatially distributed across the Mid Kildare Aquifer.*

The objectives of the investigation were to identify, quantify, and determine the incidence of trace organics in Irish groundwaters. More specific objectives are as follows:

- *identification of those trace organics most commonly encountered in Irish groundwaters;*
- *quantification of the range of concentrations of trace organics to be encountered in Irish groundwaters;*
- *identification of the incidence of trace organics in Irish groundwaters. A spatially-representative sampling programme and subsequent analysis for trace organics was undertaken on a major aquifer to achieve this objective;*
- *the drafting of a priority pollutant list of trace organics in Irish groundwaters to assist in future investigations;*
- *identification of the types of potential sources associated with trace organics which have been detected in Irish groundwaters under conditions of high vulnerability;*
- *identification of trace organic assemblages and their association, if any, with specific types of potential sources.*

Nhety one (91) groundwater samples were analysed for seventy five (75) VOCs. Ten (10) of these groundwater samples were further analysed for phenolics and PAHs and ten (10 were further analysed for PCBs and agricides. In order to supplement the study by providing groundwater quality data, additional analyses were undertaken for certain inorganic, and microbiological parameters which are traditionally used as water quality indicators.

2. INTRODUCTION

Organic compounds such as chloroform, toluene, benzene, trichloroethene, vinyl chloride, phenol, pyrene, and atrazine can originate from several apparently innocuous sources and can pose a significant threat to groundwater quality and consequently human and/or animal health. The presence of organic compounds in water in trace amounts of less than 1,000 micrograms/litre is normally imperceptible through taste or smell (organoleptically). However many frequently occurring organic compounds are bioaccumulative, persistent, and exhibit either acute (short term) or chronic (long term) toxicity with regard to human and/or animal health. Certain of these trace organics are suspected carcinogens and the World Health Organisation (WHO) have specified Maximum Allowable Concentrations (MACs) as low as 0.5 micrograms/litre in water intended for human consumption. Now consider, for example, that organic compounds are primary constituents in the following common substances in everyday use: fuels, oils, tars, preservatives, solvents, dry cleaning liquids, herbicides, pesticides, aquacides, resins, paints, lacquers, dyes, inks, explosives, preservatives, plastics, rubbers, coolants, pharmaceuticals, and disinfectants. As a consequence the following industries, activities, and/or land uses constitute potential threats to groundwater quality through formulation and/or utilisation of these substances: fuel storage, dry cleaning, landfills, printing works, leather tanneries, agriculture (all forms), forestry and wood treatment, golf courses, chemical and pharmaceutical manufacturers, coal gasification works, sewage and water treatment works, auto repair, road runoff, electricity generation and transmission, canals, mining and quarrying, and most manufacturing industries. The list is endless and seemingly innocuous activities such as the storage of home heating fuel or the application of herbicides on golf courses can have a significant effect on local groundwater quality.

2.1 TITLE DEFINITION

For the purposes of the study the title *"Trace Organic Contaminants in Irish Groundwaters"* is defined as follows: the term *"Trace"* , is used to refer to those organoleptically imperceptible dissolved concentrations of organic chemicals which are found in groundwater samples. Theoretically the upper limit is therefore defined as the maximum typical solubility of common organic compounds found in groundwater and equates to approximately 1,000 milligrams/litre or 0.1%. In practice however, only when a compound is completely soluble as in the case of acetone, or when pure undiluted organic chemicals come in direct contact with water, are concentrations of this magnitude encountered. Even in heavily-contaminated wells, rarely do the dissolved concentrations of organic compounds exceed 100 milligrams/litre unless pure product is present. The lower limit of the term *"Trace"* is determined by the detection limits of the analytical equipment used. During this study the lowest detection limits achieved were of the order of 0.01 micrograms/litre. The term *"Organic"* (expanded to organic compound) signifies a chemical formed of molecules predominately comprised of carbon (C), oxygen (O), and hydrogen (H) atoms. Nitrogen (N), phosphorous (P), sulphur (S), and other elements may also constitute part of such organic compounds. The term *"Organic"* also includes organometallic compounds such as tetramethylead - an antiknock fuel additive, and organotin - a pesticide, both of which are suspected carcinogens. The term *"Contaminant"* refers to those compounds in groundwater which are non-naturally occurring or present in non-naturally occurring concentrations. It is recognised that many organic compounds occur in nature. Salicyclic acid (aspirin), caffeine, and phenol are common examples. For the purposes of this study *"Groundwater"* is taken to refer to all naturally-occurring water within the saturated zone.

2.2 STUDY OBJECTIVES

2.21 Identification of Trace Organics in Irish Groundwaters

To *identify* the trace organics which could potentially occur in Irish groundwaters a comprehensive list of potential and commonly-occurring trace organic contaminants was drawn up from existing literature. This list is referred to as a "priority pollutant list for trace organics". It should be understood that this list is by no means final and is expected to undergo significant modification as more information becomes available.

2.22 Quantification of Trace Organics in Irish Groundwaters

Quantification of the concentrations of trace organics in Irish groundwaters originating from potential trace organic sources is evident in the results of the laboratory analyses which were undertaken during the nationwide groundwater sampling programme. The sampling area extended over the entire country and was subdivided into 27 areas (25 counties plus Tipperary N.R. and Tipperary S.R.) to facilitate research and to ensure full geographic representation. 60 sampling locations were selected from a total of approximately 200 pre-investigated wells and springs. Two sampling locations were chosen in each county and the additional six sampling locations were allocated to areas with a high potential for and/or history of groundwater contamination. The wells or springs sampled as part of the nationwide study were chosen due to their potential for contamination from a variety and/or combination of local point or diffuse sources of trace organics. The analytical results revealed water samples ranging from "trace organic free" to "heavily contaminated by trace organics". However, factors such as the persistence of the trace organic compounds, the vulnerability of groundwater to the ingress of contamination, the characteristics and transmissivity of the local hydrogeology, the solubility of the trace organic compounds, the distance and the direction from the sampling point to the source, and the depth below the water table from which the water sample was collected often obscure the relationship between the potential source(s) of trace organics and the concentration and range of trace organics detected in groundwater samples. In anticipation of these obscuring effects and in consideration of the limited number of trace organic analyses available during this investigation, wells or springs which were located a relatively short distance downgradient from potential sources of trace organics were selected for sampling during the nationwide study.

2.23 Determination of the Incidence of Trace Organics in Irish Groundwaters

An example of the *incidence* of trace organics in Irish groundwaters within a specific aquifer is evident in the results of the laboratory analyses which were undertaken during the regional groundwater sampling programme. The sampling programme was designed to spatially represent groundwater quality with respect to trace organics in groundwater beneath a specific region or area. The boundaries of a major aquifer naturally delineated the sampling area. The Mid-Kildare or Curragh Aquifer was chosen as the groundwater sampling area during the regional sampling programme. 31 sampling locations were selected from a total of approximately 100 pre-investigated wells and springs.

2.3 APPROACH

Previous studies in Ireland involving trace organics have concentrated on the analysis of public water supplies specifically for the occurrence of trihalomethanes (THMs), a byproduct of chlorination treatment, and for the seasonal occurrence of pesticides originating from the disposal of spent sheep dip in catchments recharging aquifers which provide public water supplies. Three vital ingredients were required in order to generate real data: a comprehensive list of all the trace organics which were likely to be found in Irish groundwaters; the most accurate and up-to-date analytical equipment and methodology for detecting trace organics in water samples; and representative samples of groundwater. The respective approaches to selecting the analytes, the analytical methodology, and the sampling locations were therefore critical in generating meaningful real data.

2.31 Identification of the Trace Organics

Based on experience and relevant literature, a priority pollutant list of trace organic compounds commonly occurring in groundwater was drawn up. This list provided the analytes which were likely to be detected in groundwater which in turn had the potential to be contaminated by recognised sources of trace organics.

2.32 Identification of the Analytical Methodology

The approach to the selection of the analytical methodology was similarly chosen in order to provide real results. The analytical methodology had to be based on gas chromatography and mass spectroscopy techniques in order to provide the accuracy and the necessary low detection limits required for investigation of 'part per billion' (ppb) concentrations of trace organics. As part of their programme to investigate and combat trace organic contamination in groundwater, the US Environmental Protection Agency (EPA) have standardised the methodologies permissible for trace organic analysis of water samples. The Varian Saturn II GC/MS and Tekmar LSC-2000 'purge & trap' instruments which Forbairt (formerly EOLAS) purchased during the early stages of this project were designed to carry out analyses for such trace organics using USEPA standardised methodologies.

2.33 Identification of Sampling Locations

With regard to the selection of sampling locations for the nationwide sampling programme, it was known from experience that the vast majority of water wells in Ireland provide groundwater of potable quality which would be expected to contain few, if any, trace organics. It was also realised that a random selection of merely 60 sampling locations for the nationwide sampling programmes would probably generate predominantly trace organic free samples. This would provide little real data regarding either the type and quantification of trace organics or the conditions under which trace organics would be likely to occur. Sampling locations were therefore selected which were likely to provide real data. These locations were the sites of either wells or springs situated a relatively short distance downgradient of recognisable potential sources of trace organics. In the regional sampling programme of the Mid-Kildare Aquifer it was attempted to spatially-represent groundwater at least in two dimensions by evenly distributing the sampling locations over the geographic area of the aquifer. Due to the limitations imposed by using existing wells and springs this approach did not intentionally set out to spatially represent the dimension of depth within the aquifer. However the well depths were recorded where available. The presence of potential sources of trace organics including sheep dip was recorded where present.

3. METHODS

3.1 TASK 1 - CHEMISTRY DESK STUDY

The first task during this project was to compile a list of those trace organics which it was anticipated would be detected in groundwater. This was the primary function of a chemistry desk study and was undertaken jointly by Forbairt and K.T.Cullen & Co. Ltd. This was no simple task since there are approximately 100,000 chemical substances containing trace organics registered in the EU and in Ireland alone there are nearly 3,000 pesticide formulations registered by the Department of Agriculture. However existing literature and previous investigations into trace organics provided a comprehensive list of those trace organics which were likely to be detected in groundwater. In addition certain other exotic compounds, predominantly agricides were identified during the chemistry desk study and added to the list. Some of these compounds may already have been listed as 'banned substances'. The result is a priority pollutant list of trace organic contaminants in groundwater.

The category referred to as VOCs consists of relatively light (molecularly) volatile organic compounds which are generally more soluble in water than the heavier semivolatile organic compounds (eg. solubility of benzene = 1,791 mg/l @25 degrees celsius). Typical chemicals covered by this category would include constituents in solvents, inks. dyes, aerosols, light fuels , and light oils. Many of the volatile organic compounds listed under the priority pollutant list (Table 2), although partially soluble, are believed to be relatively innocuous in trace amounts. However volatile organics such as benzene, vinyl chloride, and the trihalomethanes (THMs) are listed by the World Health Organisation as suspected carcinogens and in several cases exhibit a high degree of bioaccumulativity). Benzene is a significant constituent of petrol and certain solvents; vinyl chloride is used predominantly in the manufacture of plastics, and THMs are by-products of the chlorination of drinking supplies.

The category referred to as SOCs consists of all the heavier (molecularly) volatile organic compounds which, although less soluble in water than the VOCs, are relatively persistent, bioaccumulative, and are frequently carcinogenic. Typical chemicals covered by this category include constituents in tars, waxes, lubricating oils, coal waste, heavy fuels (including diesel), dielectric oils (formerly PCB containing), paints, agricides, and timber treatments.

Analysis for additional parameters besides the trace organic priority pollutants identified during the chemistry desk study had been requested by the Geological Survey of Ireland and agreed to. These additional parameters fall into two categories: standard inorganic water quality indicator parameters; and microbiological parameters.

3.2 TASK #2 - ANALYTICAL DESK STUDY

3.21 Priority Pollutant VOC Analysis

All 91 groundwater samples from both the nationwide and regional sampling programmes were analysed by USEPA Method #528. Many of the priority pollutant VOCs identified during Task #1 are included amongst the USEPA Method #528 VOCs. In addition, during analysis of the groundwater samples, one or two USEPA Method #528 compounds which had not been included on the priority pollutant VOC list were detected in groundwater samples. These compounds were subsequently added to the priority pollutant VOC list. Conversely however, the remaining USEPA Method #528 VOCs which were analysed for are not included on the priority pollutant VOC list. The physical and chemical properties of these remaining USEPA Method #528 VOCs have been researched subsequent to the receipt of the 91 analyses in November 1993 and none were considered appropriate for inclusion into the priority pollutant VOC list. For this reason the analysis of these compounds, none of which were detected, have not been reported.

3.22 Priority Pollutant SOC Analysis

Of the priority pollutant SOCs identified during Task #1 (including the agricides), only naphthalene was analysed for under USEPA Method #528. As discussed earlier, neither the time nor the budget was available for recalibration of the Varian Saturn II instrument for SOC analysis. However it was considered unacceptable that a study of this nature and complexity should not contain some information regarding the incidence of SOCs in Irish groundwaters. Therefore following collection and analysis of all 91 groundwater samples for VOCs by USEPA Method #528, those which contained significant concentrations of VOCs and/or those which were also located close to potential source(s) of SOCs were selected for SOC analysis. 16 wells/springs were chosen for SOC resampling. Analysis of the samples was undertaken by Simon Laboratories PLC, Llandudno, Wales.

The acid extractable and base/neutral extractable analytical package which Simon Laboratories PLC undertook was more comprehensive than that covered in the priority pollutant trace organic SOC list identified during Task #1. The package consisted of an extensive library search and quantification process. Several suspected secondary compounds which probably formed as a result of the degradation of primary trace organics were detected (eg. 6-methyl quinoxaline).

10 groundwater samples were selected for the PCB and agricide analysis package. PCBs are an extensive and complex group to analyse for and are usually subdivided for analytical purposes. The molecular structure and constituent elemental ratios are used to subdivide PCBs into Aroclors. For example Aroclor 1254, which was detected in groundwater sample DN-3, comprises several PCBs having a similar molecular structure. The same ten groundwater samples which were analysed for PCBs were analysed for certain agricides as part of a laboratory package. As with PCBs, agricides are an extensive and complex group and are usually further subdivided according to their molecular structure or elemental constituents. In order to choose the analytical packages which were likely to be appropriate to the groundwater samples selected, the potential (or suspected) sources of agricide contamination in groundwater were identified where possible. Where these sources corresponded to agricides which were identifiable on the Task #1 priority pollutant list, the respective groups in which these agricides were classified were selected for analysis. The result of the study favoured analysis for phenoxy acid herbicides, triazine herbicides, and organochlorine pesticides. Amongst the analyses eight positive detections and quantifications of agricides in six groundwater samples were made. At least one agricide was detected in each of the analytical categories chosen.

3.3 TASK #3 - HYDROGEOLOGICAL DESK STUDY

The primary purpose of the hydrogeological desk study was to identify groundwater sampling locations for both the nationwide and regional (Mid-Kildare Aquifer) sampling programmes. Since the installation of purpose-designed monitoring boreholes could not be undertaken due to financial restrictions, existing wells and springs were selected for sampling purposes. As outlined in §2.3 sampling each of the wells or springs had to satisfy certain requirements:

- a water sample collected in the well or spring had to consist of groundwater from beneath the immediate area . Groundwater being defined as subsurface water beneath the saturated zone. A sample collected from a surface water body was not acceptable even though exceptions could probably be made in karst areas.
- the groundwater sample had to be representative of the upper zones of the underlying aquifer. Wells screened at great depths are considered highly unlikely to contain trace organics except where downhole contamination has occurred. Although downhole contamination of aquifers by trace organics undoubtedly does occur and can contaminate potable supplies, it is normally a localised problem. Examples of this are when home heating oil pipelines rupture close to supply wells or industrial/agricultural effluent is actually disposed of into boreholes which are disused or used only for non-potable supplies.
- the well or spring must be capable of yielding flow rates adequate for supply purposes either potable or otherwise. Potentially brackish groundwater of the coastal margins was not excluded from the study. This groundwater is defined under S.I. No. 271 of 1992 as constituting an aquifer and a natural resource. Information as to the presence of trace organics in coastal aquifers is pertinent since many of Ireland's population centres and associated industrial zones are located on coastal margins.
- Each sampling location should have a potential for contamination by one or more recognisable sources of trace organics. This approach has been described in §2.3 and was adopted in consideration of the high cost of laboratory analysis and the limited number of analyses included in the project. Where there was a history of trace organic contamination in the area or a known source was recognisable, it was attempted to sample a well or spring downgradient and somewhat removed from the source in order to observe the effects of trace organic attenuation over distance. However, in several instances sampling locations were only available close to the source(s) and on occasion trace organic contamination of the groundwater sample was evident by odour or physical examination. Subsequent analysis of certain samples required dilution of the groundwater sample and yielded results close to saturation.
- At sampling locations where the potential for groundwater contamination had a seasonal input, it had been intended to accommodate this in the respective sampling programme. However the time constraints of the project required that all samples be collected between February and July, 1993.
- The sample collection techniques used were consistent with internationally-accepted practice (USEPA) and were intended so as to minimise the effects of interference or cross-contamination.
- VOC sample preservation consisted of maintaining the sample at <4 degrees celsius and delivery to the laboratory within 24 hours. SOC preservation was also maintained at <4 degrees celsius although sample delivery to SIMON Laboratories was extended to within 48 hours. Preservation of samples using sodium hydroxide and sulphuric acid was also undertaken where prescribed by the receiving laboratory. In the event of the samples containing suspended sediment, settling of the sediment was undertaken before decanting the sample to the container containing the preservative.
- The task of preparing a hydrogeological atlas was also undertaken as part of the hydrogeological desk study. A catchment map, a groundwater vulnerability map, a major aquifer map, and a bedrock distribution map were all prepared in digital format using existing information. In addition an isopach thickness map and a water table elevation map of the Mid Kildare Aquifer were prepared in A3 digitised format and in the hydrogeological atlas.

3.31 Nationwide Hydrogeological Desk Study

The nationwide sampling areas were equated with county boundaries, Tipperary being considered as two areas. Meetings were attended with the local authorities in each of the 27 areas. From information gained during these meetings and provided by the GSI and K.T.Cullen & Co. Ltd. files, approximately 200 possible groundwater sampling locations were identified. Locations which had a history of contamination were visited as part of a screening process often with extensive assistance being given by the local authority. Information was retained on file regarding each of the 200 potential sampling points and their locations are recorded on regional maps. Approximately 2 sampling locations per area were then selected for sampling yielding a total of 60 nationwide sampling locations. Specific information with regard to potential sources of trace organics, well constructions, groundwater flow directions, and local geology was acquired and filed. Much of this information is presented in data base format in the county maps which form part of the hydrogeological atlas and final report.

3.32 Regional Hydrogeological Desk Study

The Mid-Kildare or Curragh Aquifer was chosen as the role model in this relatively intensive groundwater quality investigation of a single major aquifer. The extent or boundaries of the aquifer represent the current GSI interpretation. 100 potential sampling groundwater locations were identified in the Mid-Kildare aquifer from information provided by Kildare County Council, the GSI (including particular assistance by Dr. D.Daly), the Department of Defence, Dr. C. Coxon, and K.T.Cullen & Co. files. Extensive hydrogeological work had recently been undertaken in preparation of the E.I.A. for the Kildare bypass and this information assisted greatly in identifying potential sampling locations and developing the maps illustrated in the Hydrogeological Atlas.

Of the 100 potential well/spring locations identified, 31 were finally selected for sampling. Where possible this selection was intended to be evenly distributed geographically over the Mid-Kildare Aquifer. The diffuse nature of one of the potential trace organic sources (sheep dip) in this area allowed geographic representation of the aquifer whilst maintaining the intention of generating useful real data. As will be discussed later in this report, trace organics originating from pesticide disposal on the Mid-Kildare aquifer were not identified during this investigation and alternative localised trace organic pollution sources are suggested from certain of the analyses undertaken by SIMON Laboratories PLC.

3.4 TASK #4 - GROUNDWATER SAMPLING AND ANALYSIS

Groundwater sampling from both the 60 nationwide locations and the 31 regional locations were collected between February and July, 1993. Sampling of the Mid-Kildare Aquifer was undertaken first. The proximity of the area to the analytical laboratory at Forbairt in Glasnevin allowed for resampling if necessary which facilitated the resolution of any initial difficulties encountered. Following completion of the Mid-Kildare Aquifer sampling programme, the nationwide sampling was initiated at the beginning of April. Repeat sampling of the 16 SOC locations began in late June, 1993.

All sampling was completed by the end of July, 1993, and the emphasis returned to gathering further information for completion of the hydrogeological desk study.

4. RESULTS

Within each programme the analytical results were divided into six relative categories of trace organic content:

CATEGORY I.D.	DESCRIPTION	RANGE (µg/l)
A	Trace organics not detected	≤ 1 µg/l
B	Very low conc. detected	≤ 5 µg/l
C	Low conc. detected	≤ 10 µg/l
D	Elevated conc. detected	≤ 100 µg/l
E	High conc. detected	≤ 1,000 µg/l
F	Very high conc. detected	≥ 1,000 µg/l

The numerical boundaries of these categories should not be considered inflexible and, where a result was marginal, other characteristics such as the nature and multiplicity of the trace organics detected are taken into account. SOC and VOC results are compounded and the sum used as the trace organic total to determine the relevant category for each sample. The standard inorganic and bacteriological results give an indication of the potability of the groundwater assuming an absence of trace organics.

The sampling locations and details of potential contaminant sources, well depths, and water table elevations were recorded during the nationwide and regional sampling programmes.

4.1 NATIONWIDE SAMPLING PROGRAMME - ANALYTICAL RESULTS

Sixty well/spring locations were sampled during the nationwide sampling programme. At least two samples were collected from the selected sampling points within each of the 27 specified areas (see §3.31). Two additional samples were collected respectively in Counties Cork and Dublin; one additional sample was collected respectively in Counties Donegal and Wicklow. The additional sampling locations were chosen to reflect both the preponderance of trace organic sources and specific sampling locations which had a history of particular trace organic contamination. Sampling locations are identified numerically in the county order in which they were sampled and are referred to with the county (area) prefix (i.e.. MH = Meath). The following is a summary of the level of concentrations of trace organics detected in the nationwide sampling programme:

A	B	C	D	E	F
CN-1	CN-2	CK-2	CW-1	CK-4	CE-1*
DL-3	CE-2	DL-1	CW-2	DN-1	CK-3*#
KK-1	DL-2	KY-2	CK-1	DN-2	DN-3*#
LD-1	GY-1	LM-2#	KE-1	DN-4*	GY-2
WH-2	KY-1	OY-1	LS-1	LK-2	KE-2
WX-2	KK-2	RN-1	LS-2	SO-2	MO-2
	LM-1	WD-2#	LK-1*		TPSR-1*
	LD-2*	WW-3#	LH-1		TPSR-2
	LH-2		MH-1*		WD-1
	MO-1#		MN-1		WH-1*#
	MH-2		OY-2#		WX-1
	MN-2		RN-2		
	TPNR-1		SO-1		
	TPNR-2		WW-2		
	WW-1#				

4.2 REGIONAL SAMPLING PROGRAMME - ANALYTICAL RESULTS

A significantly lower range of trace organic contamination is apparent from an examination of the analytical results of the Regional Sampling Programme. This was expected since the sampling locations were selected in order to geographically represent the entirety of the Mid-Kildare Aquifer. No preference was extended towards sampling locations potentially-contaminated by trace organics as was the case in the Nationwide Programme. 31 wells and/or springs were sampled and analysed for VOCs, inorganics, and microbiological parameters. In addition one sample (CUW-42) was also analysed for agricides and PCBs. The following table identifies the category of trace organic contamination of each regional sample according to its total concentration of trace organics:

A	B	C	D	E	F
CUW-2	CUW-17	CUW-5	CUW-7		
CUS-9	CUW-18	CUW-42*#	CUW-10		
CUW-15	CUW-73	CUW-44	CUW-22		
CUS-23		CUW-47	CUW-53		
CUS-29		CUW-54	CUW-74		
CUW-45		CUW-64	CUW-76		
CUS-46		CUW-66			
CUW-48		CUW-75			
CUW-50		CUW-77			
CUW-61		CUW-80			
CUW-78					
CUW-79					

5. CONCLUSIONS

- Groundwater flow directions play a crucial role in the detection of trace organics and their actual sources.
- Trace organics in groundwater occur at gross concentrations close to actual sources.
- Individual trace organics can originate from a number of sources.
- In groundwater certain trace organic sources appear to be associated with trace organic assemblages and their inherent constituent ratios.
- High concentrations of VOCs in a groundwater sample are not necessarily associated with equivalent high concentrations of SOCs. The presence of SOCs is source-controlled.
- trace organic contamination was not necessarily associated with inorganic and/or microbiological contamination. This relationship was again source-dependent.
- The trace organics frequently detected are listed below in order of incidence. Their frequency of occurence in the nationwide and regional sampling programmes respectively are given in parentheses:

naphthalene, (36 + 11)
1,2,4-trichlorobenzene, (27 + 12)
1,2,3-trichlorobenzene, (22 + 12)
1,1,1-trichloroethane, (25 + 6)
toluene, (22 + 6)

m-xylene, (19 + 3)
p-xylene, (19 + 3)
o-xylene, (20 +1)
ethylbenzene, (17 + 1)
dichloromethane, (13 + 3)
benzene, (14 + 1)
chloroform, (14 + 1)
1,3,5-trimethylbenzene, (14 + 1)
1,2 dibromo-3-chloropropane, (11 + 6)
hexachlorobutadiene, (4 + 10)
4-isopropyltoluene, (11 + 3)
1,2,4-trimethylbenzene, (13 + 1)
n-butyl benzene, (12 + 1)
1,2 dichloroethane, (10 + 0)
--10 locations
sec-butyl benzene, (9 + 0)
trichloroethene, (7 + 1)
t-butyl benzene, (8 + 0)
isopropylbenzene (7 + 0)
n propylbenzene (6 + 1)
tetrachloroethene (5 + 0)

- Those trace organics for which the cumulative sum of concentrations for all samples exceeds 50 ppb are listed below. The approximate cumulative totals are listed in parentheses for the nationwide and regional programmes respectively:

benzene (60,000 + <1)
toluene (50,000 + 30)
o-xylene (17,800 + 2)
m-xylene (17,400 + 5)
p-xylene (17,400 + 5)
--10,000 ppb
1,2,4-trimethylbenzene (9,500 + 2)
naphthalene (8,000 + 20)
1,3,5-trimethylbenzene (4,700 + 2)
ethylbenzene (4,600 + <1)
cis-1,2-dichloroethene (2,562 + 0)
sec-butyl benzene (1,600 + 0)
1,2,3-trichlorobenzene (1,500 + 30)
1,2,4-trichlorobenzene (1,200 + 30)
--1,000 ppb
1,1,1-trichloroethane (900 + 15)
1,1-dichloroethane (780 + 0)
4-isopropyltoluene (480 + 110)
n-butyl benzene (400 + <1)
Chloroform (360 + 2)
n-propylbenzene (300 + <1)
2-chlorobenzene (270 + 0)
sopropylbenzene (260 + 0)
dichloromethane (240 + 5)
1,2 dibromomethane (240 + 0)
hexachlorobutadiene (130 + 22)
1,4 (p) dichlorobenzene (136 + 0)
1,2-dichloroethane (110 + 0)
1,1-dichloroethene (100 + <1)
1,3,(m)-dichlorobenzene (100 + 0)
--100 ppb
trichloroethene (90 + 2)
t-butyl benzene (60 + 0)
chlorobenzene (60 + <1)
styrene (50 + 0)

LANDSPREADING ANIMAL WASTES

Billy Moore,
Tipperary S.R. County Council.

INTRODUCTION:

The de-exemption of agricultural developments in the 80's, the increase in water pollution incidents later in the same decade attributed to agriculture and the introduction of the requirement for the preparation of Environmental Impact Statements for intensive agricultural developments has increased the pressure on Local Authorities to respond. When Planning Authorities began to examine the available information in this area a number of apparently conflicting views emerged. Therefore it was not surprising that there was not a unified in approach to the regulation and control of agricultural developments. A Technical sub-committee was established in 1992 under the aegis of the Management Committee of the Regional Water Laboratory in Kilkenny to address this deficiency. Following discussions between eight Local Authorities mainly from the South East, Teagasc and the Geological Survey three Draft Guidance Notes were produced in 1993. These were Guidelines for i) Land Application of Animal Wastes, ii) Land Application of Blood and iii) Scoping of Environmental Impact Statements related to Piggery Developments.

Since then the Guidance Notes have undergone a number of revisions. The Notes included with this paper are the current versions and should be improved as new information comes available. The Guidance Notes represent and accommodate the many and often diverse views of the members of the subcommittee. Their input and patience is gratefully acknowledged. In this paper the emphasis will concentrate on the land spreading of wastes with particular emphasis on agricultural wastes though the principals discussed are relevant to all organic wastes applied to agricultural land.

LAND SPREADING - THE SUSTAINABLE OPTION.

Application of agricultural manures and wastes to farmland is the most economical, practical and environmentally sustainable management strategy. It also can be an effective strategy for other organic wastes, such as sludges and food processing wastes. Application of organic wastes, such as these, to the land recycles valuable nutrients and organic matter. However, care must be exercised when applying these wastes to land in order to minimise pollution risk while maximizing the beneficial effects.

Land spreading of manures and wastes should not pose undue pollution risks, despite these difficulties, when designed and managed "properly". Important aspects of proper design and management include site selection, applying wastes at the correct rates, at the right time and using appropriate spreading technology. Hydrological, agronomic and soil science principals govern the design and management of land application systems for wastes. The capacity of a soil to retain "plant-usable" moisture is defined as available water capacity. In general, fine textured soils, such as clays, have low infiltration but high available water capacities. On soils of this type, run-off to surface water following application of animal wastes is the major pollution threat (particularly in relation to BOD and P). Elevated phosphate levels in surface waters can result in eutrophication and the problem is exacerbated in lakes and slow moving waters and it is generally a slow gradual process. The higher the P-level in the soil, the higher the P-concentration in the run-off. Special care should be taken where surface waters adjoining land spreading areas show elevated background Orthophosphate levels (i.e. greater than 0.1 mg/l).

The Local Government (Water Pollution) Ammendment) Act, 1990 contains a Bye Law provision (Section 21) which empowers the Local Authority to regulate or prohibit specified agricultural activities on practices where they consider it necessary to do so in order to eliminate or prevent water pollution. Bye Laws could be made in respect of activities such as the storage and disposal of agricultural wastes or the use of manure, fertilisers and pesticides.

GROUNDWATER POLLUTION:

The land application of animal wastes can pose a risk to groundwater from Nitrate and microbiological contamination in particular. The risk to groundwater depends on the management practices and the pollution loading involved and also on the 'vulnerability' in geological and hydrogeological terms of the land spreading area.

The soil and subsoil are an excellent media for treating and attenuating contaminants provided they are not overloaded from either a hydraulic, organic or nutrient point of view. Application rates that exceed the storage capacity of the soil profile may result in leaching and the transport of dissolved pollutants downwards to groundwater. Light, Coarse textured soils (such as sands, gravels and sandy tills) have high infiltration rates but low available water capacities. On such soil types there is a relatively low run-off risk but there is a relatively high potential for leaching of nutrients or microbial contaminants to groundwater.

Loss of Nitrate to groundwater is not regarded as a serious or widespread problem in Ireland and wells with Nitrate levels in excess of the EU Maximum Admissible Concentration (MAC) are uncommon. Microbial contamination is a more common problem from agricultural wastes and the waste storage facilities pose a greater risk to groundwater than land application. One of the main problems with assessing Landspreading proposals is the wide variability in soil characteristics (e.g. depth and type) even within short distances. On-site investigation is essential in order to assess sustainability of land spreading proposals for wastes. Whereas most agricultural land is generally suitable for land application of waste, certain areas are not and the Guidance Notes offer some "Rules of Thumb" which make reference to desirable depth of soils required in high risk situations.

AIR POLLUTION:

Air pollution can be attributed to the following main areas:-

1. **Odour Nuisance:**

   Objections to intensive animal rearing proposal are frequency related to the odours which accompany land application of slurry. Odours are caused by gaseous compounds produced from the incomplete anaerobic microbial breakdown of organic matter (carbohydrates, proteins and fats) and some 150 different compounds in slurry cause odour. The creation of a nuisance is an offence under Section 24 of the Air Pollution Act, 1987. Application of "Best Practicable Means" can be used as a good defense. Reasonableness and common sense are important elements in this regard and the principle of "Shared Responsibility" applies. The method of application can have a significant impact. Only about 5% of odorous emissions emanate from spreading process and 95% of the odours are emitted from the waste following land spreading. Thus incorporating wastes immediately after application or using injection equipment will normally reduce odours to acceptable levels. Application methods and separation distances are suggested in the Guidance Notes in order to reduce odour nuisance.

2. **Ammonia (NH3) Volatilisation:**

   In the context of overall ammonia releases to air, which contribute to acid rain, landspreading of animal wastes does not have a significant impact on the environment. However ammonia losses via volatilisation and de-nitrification are causes for concern and Teagasc are carrying out further research in this area and will be making recommendations on how to reduce these losses.

3. **Spread of Disease:**

This is an issue of some concern in relation to land application of wastes but more particularly in the case of blood. It is not suggested that land application of blood represents the best practicable environmental option (BPEO) but it is likely that significant amounts of blood will continue to be applied to land for the foreseeable future. Accordingly the Guidance Notes offer some advice in relation to reducing the risk of pathogen spread and also minimising odour nuisance.

GUIDANCE NOTES:

GENERAL APPROACH:

Animal manures and wastes have been applied to the land as a source of nutrients and organic matter for all of recorded history. It is in everyone's interest that agricultural practices, including land application of wastes, are 'sustainable' and that environmental protection is seen as an integral part of the process. In any 'hirarchy' of preferred waste management options reuse or recycling is always near the top of the list. There can be few better examples of this then the land application of animal wastes and the multi-beneficial aspects of such practices have been clearly demonstrated. Soils are available as attenuation media but more importantly as nutrient resevoirs for assisting crop growth. It is crucial that the approach to land application of animal wastes moves away from waste disposal and towards nutrient utilisation. The preferred approach is towards Nutrient Management Planning which offers a sustainable solution to the problem.

Nutrient Management Planning incorporates the following elements:-

1. The fertility status of the soil, determined by analysis.

2. The nature and depth of the soil and subsoil, the principle determinants of groundwater vulnerability.

3. The nutrient content of the waste.

4. The nutrient requirement of the proposed crops.

5. Aspects of application, including nutrient application rates, timing methods and weather factors.

The key component in this approach is the farmer who by adopting a Total Quality Management (TQM) approach can ensure that nutrient management is undertaken to best economic advantage and that pollution is avoided. In Ireland, unlike countries like the Netherlands where stocking rates are 5 times higher, there is an overall defect of manures which has to be made up using artificial fertilisers.

ASPECTS ADDRESSED:

The Guidance Notes offer advice to the farmer and the Local Authority personnel in the following general areas:-

1. Storage requirements for wet and dry areas.
2. Preferred spreading periods, to coincide with crop growth.
3. Spreading rates.
4. Restrictions on spreading including separation distances.
5. Application methods.
6. Measures to reduce the risk of disease spread.
7. Measures to reduce odours.

CONCLUSIONS:

'Sustainability' in the context of agricultural practices in general and landspreading of wastes in particular will only be achieved if there is a change in approach away from land application as a waste disposal method towards Nutrient Management Planning (NMP). This approach requires the adoption of a Total Quality Management (TQM) approach and in this regard the key player is the farmer. With an overall net national deficit in manures, Nutrient Management Planning will result in both economic and environmental benefits.

Reliance on the 'command and control' approach where legislative provisions are relied upon can cause problems for both the Local Authority and the farmer. We are a long way from having to introduce the type of draconian measures which have been put in place in the Netherlands, for example.

It is in the national interest that agricultural and landspreading wastes fall into the category of sustainable practices and it is hoped that the Guidance Notes offer some assistance to the parties involved. These Notes should now be appraised critically and amended as appropriate.

major contributors in several recent water quality reports - Lough Deg, Lough Conn, Lee catchment and the Monaghan Agricultural Waste Management Study.

On the positive side, the ERU report showed a decline in the percentage of seriously polluted rivers from 7% to 3% in the same period. This reflected greater control of discharges , particularily from point source to water. In the case of farming over #1 billion has been spent since 1987 on improving the structural facilities on farms to store and handle manures and wastes.

The national organic and nutrient load associated with both municipal and agricultural wastes in Ireland has been quantified. Agricultural accounts for almost 83% of the annual national BOD and phosphorus loads with the remainder attributed to municipal wastes.

The Irish Environment Action Programme for the 1990's committed the Government to an expenditure of #230 million on wastewater treatment plants on inland waters. The EU Urban Wastewater Treatment Directive requires the plants be in operation by the years 2000 or 2005 as appropriate. Therefore, the nutrient inputs from municipal sources can be expected to decline in the coming decade. Equally the Environment Protection Agency will provide greater control of the discharges from industries through licensing. Therefore in terms of water pollution agriculture represents the largest single threat.

Controlling agricultural pollution requires an interdisciplinary approach that combines the expertise of Engineers, Agronomists, Soil Scientists and in some situations, Biologists. The water pollutants of primary concern from agriculture include nutrients, N and P, and organic matter.

Agricultural pollution derives both from point (i.e. well-defined) sources around the farmyard, such as slurry tanks, and from non-point (i.e. ill-defined or diffuse) sources, such as fields or portions of fields. The same physical, chemical and biological principles used to control industrial and municipal sources of pollution are applicable to agricultural sources, but must be applied in the context of an open, uncontrolled and variable environment instead of a controlled treatment system. Further, the techniques used to minimise pollution risk from the two types of agricultural pollution sources are different, although a Total Quality Management (TQM) approach is a basic requirement for the success of all methods.

ANIMAL WASTES GUIDANCE NOTE 1

Date: 6th August, 1993.

GUIDELINES FOR LAND APPLICATION OF ANIMAL WASTES:-

Introduction

These guidelines may be used in order to assess management strategies for the land application of animal waste both for existing and proposed developments. It is envisaged that the guidelines will assist both the farmer and the Local Authority in assessing the farmers' waste management plan.

It is accepted that landspreading is an economical and sustainable management operation for the utilisation/disposal of animal wastes, provided the landspreading strategy adopted prudently ensures the safe recycling of the nutrients for crop production thereby minimising the pollution risk.

Storage

The actual requirements for slurry storage depend on the length of the winter period when unfavourable soil or weather conditions create a high risk of pollution from land spreading.

In general minimum storage requirements are as follows:

(a) Drier Areas	16 weeks
(b) Wet or medium risk areas	20 weeks
(c) Extremely wet or high risk areas	24 - 26 weeks

It is generally considered that 16 weeks storage is likely to be unacceptable in the case of pig slurry and where in certain cases 16 weeks storage is proposed for cattle slurry justification will be required by reference to soil types and meteorological conditions.

Spreading Periods

It is difficult and in many cases unnecessary to define calendar dates governing the land application of animal wastes. The application of any nutrients (whether animal wastes or inorganic fertilisers) should preferably coincide with the periods of plant growth so that the nutrients will be utilised by the growing crop. Application of wastes should be avoided when soil conditions prevent infiltration and heavy rain is forecast within 48 hours. This matter is addressed in the AGMET booklet entitled "Weather, Soils and Pollution from Agriculture", 1992, a copy of which can be obtained from the Metrological Service in Dublin.

Preferred application periods:

(i) Grassland

(a) February/early March for first cut silage or for grazing.
(b) After first cut silage (20th May - Mid June).
(c) After second cut silage (1st - 14th July).
Application following silage cuts should preferably be within 7 - 10 days.

(ii) Tillage

It may be necessary to spread slurry in late Autumn (e.g. late October/November) but this should be avoided where practicable.

Where possible slurry applications to tillage crops (e.g. wheat, fodder, beet etc.) should be made earlier (i.e. spring) rather than later in the year.

Spreading Rates

The rate of spread of slurry should match the nutrient requirement of the growing crop. This is determined by the crop type and existing nutrient levels in the soil.

Guidelines are set out in the publication "Soil Analysis and Fertiliser Recommendations" published by An Foras Taluntais".

In general the following guideline application rates apply:-

	Cattle Slurry	**Pig Slurry**
(a) Maximum Annual Application	55 t/ha (5,000 gallons/acre)	35 t/ha (3,000 gallons/acre)
(b) General Maintenance Requirement (grassland application)	35 t/ha (3,000 gallons/acre)	17 t/ha (1,500 gallons/acre)

Where pig slurry (or chemical fertilizer) is applied to land in addition to cattle slurry care should be taken where existing soil P-level is above 15mg/kg. In no case should pig slurry be applied where the application would cause the soil P-level to exceed 30 mg/kg. In general pig slurry should not be applied to land where the existing P-level is above 15 mg/kg and there is a risk of surface water contamination from run-off. Soil phosphorus (P) levels shall be determined by the modified Morgan's P-Test as used by Teagasc.

Nitrate leaching to groundwater can be a problem in areas of free-draining soils, subsoils and bedrock. Late autumn or winter spreading of fertilisers or animal waste should be avoided. In any area designated as a "vulnerable zone" under the EC Nitrates Directive the total nitrogen application rate from animal wastes should not exceed 170 kg/ha/year in that zone. Where vulnerability is high it may be advisable to apply the limit of 170 kg N/ha to total nitrogen inputs from artificial fertilisers and animal wastes.

Restrictions On Spreading

1. Animal slurries in general should not be applied:

(a) on wet or waterlogged lands.
(b) on frozen or snow covered lands.
(c) on exposed bedrock.
(d) within 15 metres of exposed cavernous (karstified) limestone or karst limestone features such as swallow holes and collapse features.
(e) where permeable bedrock is overlain by shallow (i.e. less than 1 m from the surface) free draining subsoils, such as sands, gravels and sandy tills. Where the bedrock is limestone or dolomite a greater depth of subsoil (i.e. 2 m) is desirable.
(f) Where the water table is within 1 m of the surface in free draining areas.

2. The following minimum "safety strip" distances are suggested:

Description	**Minimum Distance (m)**
Sensitive Buildings (hospitals and schools)	200
Dwelling houses	100
Watercourses and drains	10
Wells, springs and water supply sources	50 - Domestic Wells 50 - 300 - Public Water Supplies * Note 1 (depends on vulnerability).
Public Roads	10
Main River Channels and lakes	20 (depends on slope etc.).

In general slopes of less than 6% are not considered of significance in the above.

Spreading Methods

The recommended spreading methods for all slurries is low trajectory splash plate (LTSP). Where the spreading of pig slurry is likely to cause an odour nuisance the recommended spreading method is bandspread.

Guidelines to Reduce the Risk of Disease Spread:

1. Where slurry is used on grassland it should preferably be applied to silage areas.

2. Where slurry is used on grass that is to be grazed:
   (a) it should be stored for at least 60 days
   (b) the grass to which it is applied should not be grazed for at least 30 days after application
   (c) the area should be grazed by adult or immune animals
   (d) high application rates to be avoided.

3. Where practicable slurry may be spread on tillage areas and slurry should not be used on crops which will be used for fresh human consumption.

4. Where cattle slurry comes from a farm know to have a TB infection problem, special precautions should be taken.

Guidelines to Reduce Odour Emissions:

1. Slurry should be spread using a low trajectory splashplate.

2. Slurry spreading should be avoided when the wind direction is towards population centres or neighbouring houses.

3. Slurry spreading should be avoided at times when the risk of causing odour nuisance to the public is greatest (e.g. weekends or public holidays).

4. Where slurry is spread on tilled soil or land that is to be ploughed it should be incorporated into the soil as quickly as possible following application.

Note:- If the above guidelines are followed the risk of water pollution (surface or ground water) and nuisance will be minimised.

Further reference should be made to the following:

1. Teagasc Code of Good Practice for Slurry Spreading.

2. AGMET publication "Weather, Soils and Pollution from Agriculture", 1992.

3. MAFF "Code of good agricultural practice for the protection of water".

4. MAFF "Code of good agricultural practice for the protection of air".
The above Codes are published by the Ministry of Agricultural Fisheries and Food and copies are available free of charge by writing to MAFF publications, London SE 997 TP.

5. An Foras Taluntais publication "Soil analyses and fertilisation recommendations" (latest edition).

6. GSI Report, August 1991 "Impact of landspreading of manures and other organic wastes on ground water".

Reference should also be made to any existing Aquifer Protection Plan for the area.

ANIMAL WASTES GUIDANCE NOTE 2

DATE: 6th August, 1993

GUIDELINES FOR LAND APPLICATION OF BLOOD

Introduction

Blood differs from animal wastes (i.e. slurries) in the following respects:

(a) it has a higher nitrogen (N) content (i.e. approximately 4.5 times that of cattle slurry).

(b) Phosphorus (P) and Potassium (K) levels are relatively low.

(c) the odour problem generated from land application is significantly greater than that generated from slurries particularly where the material is not fresh.

(d) blood also has a significantly high BOD (150,000mg/l).

The preferred method for disposal of blood is rendering or other processing. However, it is envisaged that for the foreseeable future significant amounts of blood will continue to be applied to land, and these guidelines are included to assist both land application operators and Local Authorities in order that the risk of environmental damage is minimised.

Spreading Periods:

Unlike animal wastes (e.g. slurries) the storage of blood may not always be practicable. Spreading of blood should preferably coincide with the pattern of crop growth (i.e. during spring or early summer). Spreading of blood on very free draining soils during the winter months should be avoided because of the high risk of nitrate leaching.

Spreading Rates:

The preferred approach is to match the nutrient supply in the blood to the requirements of the growing crop. If the nitrogen supply, from the application of blood, is greater than the crop's requirement the surplus nitrogen may leach, particularly on the lighter soils. On heavier soils the risk of nitrate leaching is significantly smaller.

A typical application rate of 7 t/ha (i.e. 630 gallons/acre) per silage cut is suggested. It is not generally recommended that blood is applied to land which will be used for grazing. In all cases (including cereal crops) a maximum annual application rate of 10 t/ha is recommended. The blood may need to be diluted with water to practically achieve the low application rates.

On lands where blood is applied on a regular basis it is recommended that a programme of soil, ground water and surface water monitoring be put in place. The above monitoring is particularly important where animal wastes or artificial fertilisers are applied to the land in addition to the blood.

In any area designated as a "vulnerable zone" under the EC Nitrates Directive blood should not be applied.

Restrictions On Spreading:

1. Blood in general should not be applied:

(a) on wet or waterlogged lands.
(b) on frozen or snow covered lands.
(c) on exposed bedrock.
(d) within 15 metres of exposed cavernous (karstified) limestone or karst limestone features such as swallow holes and collapse features.
(e) where permeable bedrock is overlain by shallow (i.e. less than 1 m from the surface) free draining subsoils, such as sands, gravels and sandy tills. Where the bedrock is limestone or dolomite a greater depth of subsoil (i.e. 2 m) is desirable.
(f) Where the water table is within 1 m of the surface in free draining areas.

2. The following minimum safety strip distances from designated structures should be applied:

Description	**Minimum Distance (m)**
Sensitive Buildings (hospitals and schools)	200
Dwelling houses	100
Watercourses and drains	10
Wells, springs and water supply sources	50 - Domestic Wells 50 - 300 - Public Water Supplies * Note 1 (depends on vulnerability).
Public Roads	10

3.4 Types and quantities of wastes and emissions generated including slurries and other contaminated effluents, solid wastes including animal carcases and air emissions.

3.5 Details of proposals for slurry storage including capacities, construction details, etc.

3.6 Slurry disposal proposals including land use requirements and area of reserve land available. The details should incorporate crop rotation proposals. Land application machinery to dispose of slurry should be clearly specified.

3.7 Details of slurry disposal plant and equipment owned by or available to the developer.

3.8 Copies of binding legal contracts for slurry spreading signed by landowners/occupiers and developers to be submitted.

3.9 Details of all services required to facilitate development.

3.10 Details of proposed feedstuff indicating any heavy metal content (e.g. copper and zinc).

3.11 Developer shall specify maximum soil contaminant concentrations which will be regarded as performance standards and incorporated into the Waste Management Plan.

SECTION 4: DESCRIPTION OF ALTERNATIVES:

4.1 Alternative sites considered.

4.2 Alternative site layout and designs considered (e.g. overground verses underground storage, shallow verses deep tanks, etc.)

4.3 Alternative processes considered (including land application methods).

4.4 Reasons associated with each decision taken in the consideration of the alternatives above should be stated.

SECTION 5: DESCRIPTION OF EXISTING ENVIRONMENT:

5.1 Location of Structures:

5.1.1 Details of site investigation carried out including trial pit in order to assess suitability for proposed unit. This should include depth of water table and springs, etc.

5.1.2 Details of load bearing capacities of soils.

5.1.3 Description of access and road network incorporating traffic levels.

5.2 Land spreading area:

5.2.1 O.S. Maps showing full extent of land proposed for slurry spreading (preferably to scale of 1:10,560 or 6" to 1 mile) indicating:

5.2.1.1 - Spreading area outlined/shaded in red.

5.2.1.2 - All watercourses, streams and rivers and all wells, springs and boreholes (within spreading area and within 200 m of land boundaries) shown in blue. All sources of public water supply or groups schemes within 300 m to be shown.

5.2.1.3 - All property including dwelling houses, institutional buildings, industrial premises, etc., within spreading area and within 200 m of spreading area to be shown in green.

5.2.1.4 - Locations of archeological monuments and areas of scientific interest should be shown in brown.

5.2.1.5 - All unsuitable land within and adjacent to proposed spreading area to be clearly shown.

5.2.1.6 - Excluded spreading areas should be clearly identified (e.g. cordon sanitare 100 m to residential properties, quarries, springs, etc.) Details of proposed spreading quantities of other slurries being landspread in the area to be submitted.

5.2.1.7 - Legal owners/occupiers of land spreading areas outlined to be clearly shown.

5.2.2 An independent study to be carried out by a reputable expert consultant to assess the nature of soil, surface water, groundwater and their inter-relationships in the areas in which it is proposed to spread the waste.

The following items should be examined:

5.2.2.1 - Types and depths of soils and subsoils.

5.2.2.2 - Hydrogeological information on depths to bedrock and groundwater in the area.

5.2.2.3 - Direction of groundwater flow.

5.2.2.4 - Qualitative assessments of soil and subsoil permeability.

5.2.2.5 - Appraisal of aquifer category and reference to local aquifer protection policy or plan (where available).

5.2.2.6 - Presence or absence of karst features if bedrock is limestone.

5.2.2.7 - Slopes and surface water runoff susceptibility.

5.2.2.8 - Local climatology and hydraulic loading capacity of soils.

5.2.2.9 - Existing land use and cropping history.

5.2.2.10- Existing nutrient levels and chemical loading capacities of soils (i.e. soil fertility survey).

5.2.3 A baseline study should be carried out of all waters (surface and groundwater) which could be affected by the development.
Such a study should address the following:

5.2.3.1 - Water quality. As a guideline this should include physical, chemical and biological quality of streams and rivers and chemical and microbiological quality of groundwater.

5.2.3.2 - Details of all beneficial uses of waters.

5.2.4 An assessment of existing air quality in the area.

5.2.5 An assessment of existing noise levels in the area.

5.2.6 An assessment of existing traffic levels in the area.

*<u>NOTE:</u> **Some of the above information may be available from public authorities and may be compiled by desk study.
It is suggested, as a guideline, that soil sampling be carried out at a rate of 1 sample per 4 hectares (1/10 acres). Each soil sample to be a composite of 20 cores.
Similarly trial pits to a depth of 2.5 m (or to rock) should be carried out at a rate of 1/10 hectares (1/25 acres), subject to a minimum of 1 per landholding. This rate may be increased or decreased as appropriate (depending on geological and hudrogeological information available, aquifer vulnerability etc.).**

In certain circumstances if a borehole is not already in existence in the area a minimum of one borehole may be required (in practice, this borehold may be used subsequently for monitoring).

Reference should be made to National Soil Survey Data, to available geological information and for the Teagasc run-off vulnerability map (prepared by Tim Gleeson).

SECTION 6: DESCRIPTION OF IMPACTS AND MITIGATION MEASURES:

6.1 Structures:

6.1.1 An assessment of the impact of the proposed structures particularly in relation to landscape and visual aspect and description of mitigation measures including screening, tree planting, external finishes, etc.

6.1.2 An assessment of the impact of slurry storage structures on ground and surface waters. Quality control measures to be specified.

6.1.3 An assessment of the noise generated by the development.

6.1.4 An assessment of the odours and emissions generated by the development.

6.1.5 An assessment of the traffic generated by the development.

6.1.6 An assessment of the likely animal fatality rates and details of proposed method of storage, transport and disposal.

6.1.7 Proposals to deal with accidental spillages including notification procedures.

6.2 Landspreading:

6.2.1 A Nutrient Management Plan for the landspreading areas. This includes an assessment of the relationship between slurry application rates, crop nutrient requirements and existing soil nutrient levels. This should clearly indicate the total land use requirement and should take account of other slurries being landspread in the proposed landspreading area. The extent of the 'reserve' landspreading area should be indicated. Reference should be made to any impact of slurry spreading on the soils including increase in heavy metal content (e.g. copper & zinc).

6.2.2 An assessment of the impact of the slurry disposal on the quality of surface and groundwaters.

6.2.3 An assessment of the impact on air quality of the proposed slurry disposal methods.

6.2.4 A Waste Management Plan incorporating all of the landholdings should be submitted. This should incorporate a Slurry Spreading Register.

6.2.5 Proposed mitigation measures should be submitted which should, at a minimum, address the following:

6.2.5.1 - Reduction of odour emissions.

6.2.5.2 - Preferred periods and rates of spreading in order to avoid excessive soil nutrient build up, surface runoff and contamination of groundwater.

6.2.5.3 - Reduction of risk of disease spread.

6.3 **General:**

6.3.1 An assessment on the impact on flora and fauna in the area. It may be necessary that consultation take place with the National Parks and Wildlife Service of the Office of Public Works.

6.3.2 An assessment on the impact on archeology and cultural heritage in the area. It may be necessary that consultation take place with the Archaeology and National Monuments Section of the Office of Public Works.

6.3.3 An assessment of the impact caused by increased traffic volume generated by the development in the area.

SECTION 7: MONITORING:

7.1 **Groundwater:**

The developer shall indicate a monitoring programme to assess any impact on groundwater quality beneath and adjoining the land spreading area. It may be appropriate to install up-gradient and down-gradient monitoring wells for such monitoring purposes. The extent and frequency of the monitoring shall take account of aquifer vulnerability factors.

7.2 **Surface Waters:**

The developer shall indicate a monitoring programme to assess any impact on surface water quality in the area. The sampling and analysis programme shall include physical, chemical and biological parameters.

7.3 **Soils:**

Evaluation of the soils at appropriate intervals (to be determined by the L.A.) shall be carried out in order to assess the nutrient levels in the soils and any build up of contaminants including heavy metals.

OCCURRENCE AND DISTRIBUTION OF GROUNDWATER IN NORTHERN IRELAND

N S ROBINS

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

ABSTRACT

Groundwater is present in all the geological formations of Northern Ireland, albeit only in modest quantities in the older rocks. Recharge is inhibited by the widespread cover of till, but this is counteracted to a large extent by the high effective rainfall which promotes some summer recharge. Both the Sherwood Sandstone Group and the Chalk are productive aquifers at outcrop, but offer modest hydraulic properties where they are concealed by younger rocks. Infiltration ranges from about 50 mm a^{-1} over the weakly permeable basement rocks to as much as 500 mm a^{-1} where rare granular soils occur over permeable superficial strata or bedrock aquifers.

INTRODUCTION

Groundwater may provide about 110 Ml d^{-1} out of some 750 Ml d^{-1} in public and private supply, nearly half of which is consumed in the Greater Belfast area. Although the groundwater contribution is small, the widespread occurrence of groundwater as a resource ensures that it retains a significant social and economic value. Currently, both agricultural and industrial consumers are keen to develop private groundwater supplies to combat rising non-domestic charges for public supply water.

The availability of groundwater in Northern Ireland is controlled by four important factors:

- relatively high effective rainfall of about 500 mm a^{-1} (Wilcock et al, 1978) distributed throughout a large part of the year;
- widespread distribution of clayey till and gley soils;
- the potentially productive aquifers are largely concealed by low permeability strata;
- small compartmentalised aquifer units.

The first two tend to counteract each other. The gley soils which occur in conjunction with the till are maintained at or near field moisture capacity for a large part of the year in many areas and this allows summer recharge to occur under favourable conditions at some sites. Although intergranular transport undoubtably takes place through the unsaturated till, by-pass routes via interconnected sandy lenses and even sub-vertical fractures play an important part in the recharge process. Topographic lows, where surface water tends to collect, offer more favourable conditions for recharge than interfluves where runoff is dominant. Recharge is also provided to the Visèan limestones and the Chalk via sink holes.

The last two factors combine to inhibit the regional value of groundwater; there are no major aquifers of regional significance, although Bennett (1979) suggested that abstraction from the Sherwood Sandstone Group in the Lagan Valley may have reached as much as 33 Ml d^{-1} during the 1930s. However, the greater part of this aquifer, which has a total area of about 4000 km^2, is concealed by Jurassic and Cretaceous strata and by the Antrim Plateau Basalts. The Chalk is also largely concealed, in this case by the Antrim Plateau Basalts. The hydraulic conductivity in both the Sherwood Sandstone Group and the Chalk are reduced, and recharge and availability of groundwater is restricted beneath this cover (Manning, 1972). The limited area of other potential aquifers, notably the Carboniferous sandstones and limestones encourages shallow groundwater circulation, short flow paths and modest resources.

The availability of groundwater from superficial deposits, principally glacial outwash deposits, depends entirely on the distribution of saturated medium- to coarse-grained material. A number of such deposits were successfully exploited for public supply (Price and Foster, 1974), but their value has since diminished because of the vulnerability of these shallow aquifers to surface pollutants.

GROUNDWATER AVAILABILITY

Northern Ireland offers the most compact and diverse range of solid geology, Quaternary deposits and soil types anywhere in Europe. The south-westerly Caledonide extension of the Scottish Midland Valley graben divides the Upper Palaeozoic and younger strata from the Precambrian rocks to the north, largely under the cover of the Antrim Plateau Basalts, and the Lower Palaeozoic rocks to the south, the latter situated to the south-east of the line of the Lagan Valley. The principal aquifer units occur between the Precambrian in the north and west and the Lower Palaeozoic rocks in the south and east of Northern Ireland.

The hydrogeological map of Northern Ireland (BGS, 1994) indicates that the most favourable hydraulic properties are found at outcrop in the Permian and Triassic sandstones and limestones, the Chalk and Hibernian Greensand and the Viséan Upper and Lower Limestone. That being so, the distribution of private supply boreholes identified in a borehole and well inventory carried out recently for the Department of Environment for Northern Ireland (Table 1) indicates that the areal

TABLE 1 Private groundwater use - numbers of boreholes identified in the BGS inventory study for each aquifer unit

Geology	Agriculture	Industry	Domestic	Other	Total
Palaeogene	188	35	26	18	267
Cretaceous	7	0	1	1	9
Triassic	44	4	3	11	62
Permian	0	0	0	0	0
Upper Palaeozoic	23	3	3	4	33
Lower Palaeozoic	99	5	6	20	130
Precambrian	25	1	7	7	40

size and distribution of each aquifer unit outweighs its hydraulic properties in terms of groundwater use. Indeed, the Palaeogene, principally the Antrim Plateau Basalts, and the generally weakly permeable Lower Palaeozoic rocks are exploited by the largest number of boreholes.

The distribution of boreholes between aquifer units belies the availability and the occurrence of groundwater. The same survey of boreholes clearly shows that the Triassic (Sherwood Sandstone Group) offers the highest mean yield, followed by the Viséan Upper and Lower Limestones, with the Palaeogene offering comparatively modest yields (Table 2). These mean yields may be influenced by land use and water use with relatively modest demands in the farming areas of say the Palaeogene and the Cretaceous outcrops compared with the higher industrial demands on the Triassic.

TABLE 2 Borehole yield statistics for respective aquifer units

Unit	Number of boreholes	Yield ($l\ s^{-1}$) minimum	maximum	mean	Standard deviation
Palaeogene	143	<0.1	20	2.3	3.3
Cretaceous	5	0.8	4	2.8	1.3
Triassic	45	0.6	57	9.1	13.5
Upper Palaeozoic*	23	<0.1	10	1.5	2.1
Viséan	80	<0.1	44	6.2	8.9
Lower Palaeozoic	83	<0.1	5	1.0	0.9

* excluding the Viséan

Yield-drawdown curves, although only available for selected higher-yielding boreholes, and then not universally (Figure 1), show that borehole performance of the Sherwood Sandstone Group is modest compared to parts of the Carboniferous limestones and the Chalk. Further confirmation of this is provided by the values of formation constants derived for the respective aquifer units in Northern Ireland. Again few data are available for the less productive aquifer units, but typical values or ranges for hydraulic conductivity are (Robins, in press):

Quaternary	1 to 100	$m\ d^{-1}$
Palaeogene	0.01 to 1.0	$m\ d^{-1}$
Triassic	0.8 to 4.0	$m\ d^{-1}$
Permian	<1	$m\ d^{-1}$
Carboniferous	0.1	$m\ d^{-1}$
Devonian	<<1	$m\ d^{-1}$

The Chalk at outcrop is partly karstified and its hydraulic conductivity is consequently highly variable; Milton et al (1970) suggested a value for a site near Larne of about 50 $m\ d^{-1}$. The Viséan limestones, which offer negligible transmissive properties where fracturing is weakly developed, can also support conduit flow where karstification is well developed.

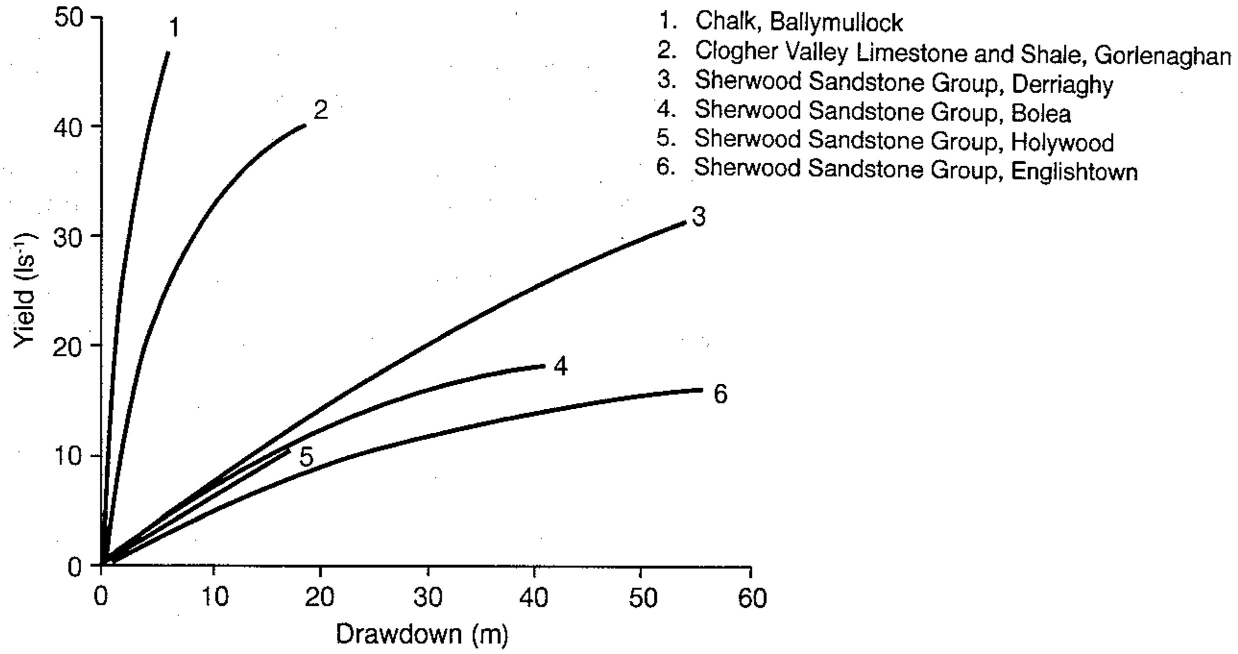

FIGURE 1 Yield-drawdown curves

PARTLY CONCEALED AQUIFERS

The contrasting hydraulic properties of the Sherwood Sandstone Group aquifer at outcrop in the Lagan Valley and elsewhere, with the concealed strata beneath the Antrim Plateau Basalts has been discussed at length by Bennett (1983) and Downing et al (1982). A similar picture can also be seen in the case of the Chalk. Wherever the Chalk is concealed by the Antrim Plateau Basalts, the depth to the aquifer is generally too great to allow significant exploitation. Besides, recharge via the basalts is limited; the porosity is reduced under the weight of overburden so that the hydraulic properties are greatly reduced away from outcrop. A 274 m borehole at Corbally Reservoir, near Portrush encountered Chalk at depth but no water was obtained. A borehole at Stoneyford, County Antrim is typical of the few successful boreholes which penetrate the concealed Chalk aquifer, in this case to a depth of between 91 and 115 m. The yield of the borehole was only 5 l s^{-1}.

That significant recharge reaches the aquifer at outcrop is indicated by the spring discharges along the Antrim coast. These range from modest discharges of 1 or 2 l s^{-1} to larger discharges, some of which have been used over the years for public supply, including:

Stradreagh, Limavady	27 l s^{-1}
Knocklayd, Ballycastle	19 l s^{-1}
Sallagh, Larne	32 l s^{-1}
The Grove, Carnlough	25 l s^{-1}

There is considerable evidence in cliff exposures along the Antrim coast that the Chalk was karstic before the onset of the Palaeogene basalt flows. There are several large rubble filled sink holes visible to the north and south of Larne, and smaller but equally distinct features can be seen at several places from the road north to Glenarm. The existence of the large coastal springs points to the exposed Chalk still being actively karstic in some areas. Campbell (1984) described a cave system in the Blackburn valley, 3 km north of Carnlough; the entrance is some 4 m high by 1 m wide in "brilliant white chalky limestone".

Barnes (1994) surveyed spring risings and river and stream sinks along Garron Point to the north of the Blackburn river. All but two of the streams and rivers that flow off the basalt onto the Chalk disappear into sinks, commonly via pools at the base of waterfalls. An estimate that at least 80 % of the water in the Chalk risings is derived from local sinks and that the remainder derives mainly from inland recharge via the basalt is based on the differential ratio of the Na: Mg ion in basalt groundwater (>4) and in river water sinks, albeit off the basalt (of about 1). An additional minor component to the risings is direct recharge at outcrop.

A detailed survey of the Larne area established that the coastal discharges in the immediate vicinity were all young groundwaters with high tritium concentrations indicative of rapid transit between recharge area (probably local) and discharge zone (Milton et al, 1970). As in the Carnlough study, little contribution of older water from the concealed inland part of the aquifer beneath the basalt cover was apparent.

GROUNDWATER TRANSPORT AND THE ROLE OF TILL

The limited areal extent of the aquifer units (at outcrop) in Northern Ireland means that groundwater flow paths are for the most part, both short in extent and shallow. Recharge into a Carboniferous sandstone or limestone unit is unlikely to find a flow path that takes it into adjacent units before returning to the surface as baseflow. The same also applies to the Triassic aquifers and for that matter all units from which useable quantities of groundwater can be extracted. The Triassic aquifer is, in any case, broken into small units by dykes and mudstone horizons. Some deeper groundwater flow does occur, but it is of limited volume (Smith, 1985).

Secondary permeability is important in all the aquifer units. Lovelock (1977) reports results from laboratory analyses of plug specimens from the Sherwood Sandstone Group. Intergranular permeability was found to be typically in the range 10^{-1} to 1 m d^{-1}, whereas field derived hydraulic conductivity values fall more in the range 1 to 10 m d^{-1}, some one to two orders of magnitude greater and indicating the important contribution that fracture flow adds over and above the intergranular flow. The extreme examples are the karstified areas of the Chalk and the Viséan Upper Limestone, in which intergranular permeability contributes little to groundwater flow and storage.

Given that flow paths are short and that fracture flow or secondary permeability is a major influence on the hydraulic properties of the aquifer units, the almost continuous cover of till in lowland areas takes on an important significance as a potential moderator of recharge. The processes involved in recharge through till are not fully understood, but there is increasing evidence from research in England to suggest that the perceived inhibiting role has in the past been overstated. Bennett (1976) suggests that recharge to the Lagan Valley sandstone aquifer can readily take place beneath the northern scarp overlooking the valley where till is absent. So it may, but it is also likely that a major contribution arrives at the aquifer via rapid by-pass features within the till, such as fractures or permeable lenses.

THE BASEMENT - A SHALLOW WEATHERED AQUIFER

It is tempting to think of the Lower Palaeozoic and Precambrian rocks as dry, or at best only very shallow and weakly permeable "aquifers". The dominance of fracture flow in controlling groundwater movement means that certain areas of outcrop may be totally devoid of groundwater in any useable quantity, but it also means that other areas may be relatively plentiful. Typical yields were described by Wilkinson et al (1908) for part of the Dalradian at Londonderry:

> "Wells for private supplies have been sunk at a few points . . one of which traversed 85 feet (26 m) of gravelly boulder clay over gravel and was made for the supply of a new house in Lisnagelvin, 1 km east of Waterside. Another was sunk at Ebrington Factory, through 14 feet (4 m) of boulder clay and 138 feet (42 m) of schist with hard grit bands, and yielded 3000 gallons per day (0.2 l s^{-1}). A third was sunk in the premises of Messrs Watts, to a greater depth than that at Ebrington, but without satisfactory results."

High, dissected relief in the Sperrin and Mourne Mountains promotes shallow groundwater flow along those fractures which offer the least hydraulic resistance via short flowpaths. Almost all of the groundwater transport takes place at shallow depths, although there may be low volume, slow, deeper circulation, which on returning to the surface has a greater degree of mineralisation than the younger shallow waters. Mixing with shallow waters near the point of emergence often disguises the presence of such deeper upwelling waters.

The volume of water in circulation within these rocks can be estimated from low-flow data for gauged catchments. The assumption is made that all groundwater flowpaths are short and that most of them terminate at the surface within the catchment above the respective gauging station. This assumption fits the smaller catchments (perhaps less than 100 km^2) better than the larger ones, and will in any event provide an overestimate of infiltration because of groundwater throughflow at the bottom end of the catchment.

Gustard et al (1992) provide seven day minimum flow rates for selected hard rock river catchments, and IH/BGS (1993) provide the respective catchment areas (Table 3). These data suggest that an average annual rate of infiltration of 60 mm a^{-1}, albeit with a standard deviation of 50, is required to sustain observed rates of low flow, which are assumed to represent baseflow. The Silurian and Silurian/granite catchments consistently receive the lowest amount of estimated infiltration with a mean of only 30 mm a^{-1}. The Precambrian catchments are highly variable with a range of 17 to 126 mm a^{-1}, which reflects the considerable variation in jointing and weathering present in these strata. The rates are small compared with estimates for more permeable aquifer units in Northern Ireland

TABLE 3 Infiltration derived from low-flow data for hard rock catchments

Catchment number	River or stream name	Geology	Catchment area (km^2)	Minimum flow (m^3 s^{-1})	Infiltration (mm a^{-1})
201007	Burn Dennet	Precambrian	145.3	0.58	126
201008	Derg	Precambrian	337.3	0.60	56
201010	Mourne	mostly Precambrian	1844.5	1.00	17
203017	Upper Bann	Silurian/granite	335.6	0.48	45
203024	Cusher	Silurian/granite	176.7	0.13	23
203038	Rocky	granite	6.7	0.03	141
205005	Ravernet	Silurian	69.5	0.03	14
205008	Lagan	Silurian	85.2	0.11	41

(eg up to 500 mm a^{-1}) and serve to illustrate the relative amount of water available in circulation within the older rocks of the Basement.

POTENTIAL DISTRIBUTION OF GROUNDWATER

Given that mean annual potential infiltration or recharge ranges from an average of about 60 mm over the weakly permeable Precambrian rocks to a maximum, defined by the effective rainfall, of 500 mm over glacial outwash sands and permeable aquifers beneath permeable soils, it is tempting to identify the intermediate situations. It should be noted that infiltration may be rejected due to the low infiltration capacity of some surface layers, many of which are quite widespread. Figure 2 offers an attempt at such a ranking exercise, using broad ranges of infiltration in order to avoid detail which cannot yet be justified given inadequate understanding of the role of the till and other weakly permeable layers, and the small compartmentalised nature of the aquifers. The distribution is compatible with available baseflow analysis (Gustard et al, 1992).

FIGURE 2 . Estimated annual potential infiltration rates

CONCLUSIONS

Northern Ireland offers a complex and diverse range of hydrogeological conditions. Its aquifers tend to be small, supporting short groundwater flow paths at shallow depths. In all aquifer units except those in superficial strata, groundwater storage and transport are heavily dependent on the occurrence of secondary permeability derived from fractures and other interconnected non-intergranular void spaces. This is as much the case in the potentially productive Sherwood Sandstone aquifer in the Belfast area as it is in the Chalk at outcrop and in the Viséan Upper Limestone.

Although the role of till as an inhibiter to recharge is not yet fully understood, it is an incomplete and leaky barrier to infiltration. Where it is absent and a permeable soil overlies an aquifer, an average of up to 500 mm a^{-1} is available for recharge. Over the weakly permeable rocks of the Basement and younger granites only about 60 mm a^{-1} is likely to infiltrate to the shallow water bearing zone of weathering. Intermediate rates apply to other strata, for instance the Palaeogene Basalt Lavas perhaps receive up to 300 mm a^{-1} in favourable locations.

The widespread availability of groundwater supplies, both large and small, ensure that the groundwater resources of Northern Ireland will always be regarded as an important social and economic asset despite the availability of abundant good quality surface water.

ACKNOWLEDGEMENT

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IMPLICATIONS OF SEWER DEVELOPMENT ON GROUNDWATER QUALITY

Bruce Misstear, Dept. of Civil, Structural and Environmental Engineering, Trinity College, Dublin

Philip Bishop, Mott MacDonald Group, Cambridge

ABSTRACT

This paper describes a current research project on the extent of groundwater contamination from leaking sewers in England and Wales. Examples of sewer-related groundwater contamination incidents are also described from the USA and Germany. The paper then addresses the situation in Ireland, and concludes that sewers need to be considered when developing a groundwater protection policy.

INTRODUCTION

The problem of groundwater pollution by sewage from septic tanks and soakaways has received significant attention in Ireland in recent years. For example, the National Standards Authority of Ireland produced a guidance document on septic tank systems for single dwelling houses in 1991 (Report SR 6:1991), and the Geological Survey of Ireland and Sligo RTC prepared a joint report *Septic tank systems and groundwater in Ireland* (Daly *et al.*, 1993). To highlight the scale of the problem, the latter report indicates that in some areas of Ireland more than 50% of wells are polluted by septic tank effluent. However, the risks to groundwater quality by sewage effluent from leaky sewers has received much less attention.

Until recently, the subject of groundwater contamination from leaking sewers had received little attention in Britain also. A current research project aims to address this deficiency, by defining the scale of the problem in England and Wales. This project will be the main subject of this paper. The paper will then summarise relevant experience from the USA and Germany, before returning to the situation here in Ireland.

Before reviewing the studies in Britain and elsewhere, it is worth summarising the main characteristics of sewage which may give rise to groundwater contamination:

- bacteria (usually measured as faecal coliforms or *E. coli*)
- inorganic nitrogen species, predominantly nitrate and ammonia
- various other inorganic major ions such as sulphate, chloride and potassium
- boron (from detergents)
- phosphate (from detergents)
- trichloromethane (from chlorination of mains water)
- chlorinated solvents and other industrial organics present in industrial effluents.

In relation to the theme of this seminar, bacterial pollution may not pose a major threat to sustainability of groundwater resources as bacterial pollutants are usually eliminated relatively rapidly in the subsurface. However, other contaminants found in sewage, such as industrial organics, are much more persistent in the subsurface and may constitute a significant risk to sustainable development of groundwater resources.

SEWER-RELATED GROUNDWATER CONTAMINATION IN ENGLAND AND WALES

The authors are currently carrying out a research contract for the Construction Industry Research and Information Association (CIRIA) entitled *Reliability of Sewers in Environmentally Sensitive Areas* (Misstear *et al.*, 1995). The objectives of the study are to define the extent of groundwater contamination from sewers in England and Wales, the causes of sewer exfiltration, and strategies for minimising problems in the future. This paper focuses on the groundwater aspects of the project.

GROUNDWATER CONTAMINATION INCIDENTS

A literature survey and questionnaire survey revealed over 50 sewer-related groundwater contamination incidents, as summarised in Figures 1 and 2. The earliest incident cited in the literature is that of Castle Springs, Bath in 1928, when a leaking sewer led to contamination of a well in a Jurassic limestone aquifer (this and other incidents or studies referred to in this paper are summarised in Table 1). This resulted in a typhoid outbreak with seven deaths. The most recent published incident (and the one for which the best information is available) was that at Bramham in Yorkshire in 1980, where leakage from a surcharged sewer contaminated a borehole exploiting the Magnesian Limestone aquifer resulting in 3 000 cases of gastro-enteritis (Short, 1988). At Bramham, a contributory factor to the outbreak of illness was a breakdown in chlorination of the supply.

As can be seen from Figure 1, the questionnaire survey yielded 42 incidents. The breakdown of incidents by aquifer (from both the questionnaire survey and published studies) is shown in Figure 3, which indicates a majority of incidents (30 in all) related to the Chalk aquifer. This is likely to reflect the Chalk's status as the most extensively exploited aquifer for potable water supply, but there are also likely to be hydrogeological controls affecting its vulnerability to sewer-related contamination. The most productive horizons of the Chalk aquifer are generally located within the uppermost 10 to 20 m of strata which have well developed fissures. Thus, in the case of unconfined Chalk, shallow contaminated groundwater may move relatively rapidly to abstraction boreholes with inadequate time for bacteria mortality.

The Triassic Sandstone aquifer is the second most important aquifer in England and shows far fewer sewer-related contamination incidents than the Chalk. This may reflect different flow mechanisms in the sandstone, with a stronger component of inter-granular flow and more regular fissuring with depth leading to slower overall groundwater velocities and therefore longer times for bacteria die-off. Following the Chalk and Triassic Sandstone, the third most affected aquifers are alluvial deposits, such as the Thames Gravels in London. The shallow nature of these deposits makes them vulnerable to contamination, but they are not generally exploited for potable water supply.

All the affected aquifers are generally unconfined with occasional permeable Drift cover. A high water table also seems to be common to many incidents. None of the incidents (apart from the published Bramham incident of 1980) resulted in any deleterious effect on public health. This was generally due to the adequacy of chlorination of raw water at source and the fact that many sources were taken temporarily out of supply when a bacteriological problem with raw water was recognised.

The causes of sewer exfiltration quoted in these contamination incidents are varied, including:

- surcharging (frequently associated with blockages)
- poorly constructed laterals/lateral connection (often to private sewers)
- fracturing
- leaking joints.

The causes of leakage will be covered in detail in the CIRIA report.

URBAN GROUNDWATER QUALITY

The literature and questionnaire surveys also collated information on whether leaking sewers were implicated in urban groundwater quality degradation. There is circumstantial evidence that sewer leakage contributes to high nitrate concentrations in many conurbations, particularly Liverpool and Birmingham. Nield (1986) states that water being pumped out of the tunnel at the Central Station, Liverpool has three times the UK limit for nitrates as the result of sewage pollution. Halliday and Lerner (1992) state that shallow groundwater sampling in Birmingham shows sewer leakage to be one highly probable source of sulphate, chloride, phosphate and nitrate contamination.

COMPLETION OF CIRIA PROJECT

The full CIRIA report on leaking sewers and groundwater contamination will be published in the next year. The strategies for minimising future pollution risks are at present being finalised but are likely to include strategies for:

- existing sewers, ie inspection and maintenance in environmentally sensitive areas
- new sewers in environmentally sensitive areas
- groundwater monitoring
- borehole construction.

INTERNATIONAL EXPERIENCE

As part of the CIRIA project, an extensive literature search was carried out for incidents of sewer-related groundwater contamination internationally, with the main focus of attention being the USA and Continental Europe. Figure 4 summarises the number of published studies on sewer-related groundwater contamination for each country. It can be seen that by far the most published studies are from the USA and Germany; this probably reflects the importance of groundwater in both countries. Figure 4 also shows one incident for Ireland: this is Naas pollution incident, described later in this paper.

AMERICAN STUDIES

The earliest reference found to sewers as a source of groundwater contamination from the USA was that of Deutsch (1963). Deutsch describes two cases of leaking sewers polluting groundwater in Michigan in 1945 and 1952 (Table 1). In 1945, the Michigan Department of Health recommended that the city of Sturgis abandon its wells, or install a chlorination system, because of the proximity of sewers to wells and bacteriological contamination of well water. In 1952, a sewer on a small industrial plant in the Lansing area fractured, apparently from frost-heave, permitting sewage to flow to a well. As a result, six employees of the plant became ill.

Various studies from the USA point to the relevance of sewer leakage as a source of organics pollution in industrial areas (eg Avon and Bredehoeft, 1989).

GERMAN STUDIES

In Germany, Hornef (1983) appears to have been among the first to recognise the connection between leaking sewers and groundwater contamination. Merkel *et al* (1988) estimated that 2% leakage of sewer flows occurred in the Munich Harlaching area, contributing phosphate, boron, total organic carbon and a variety of chlorinated solvents to groundwater. Mull *et al.* (1992) similarly concluded that sewers were a source of groundwater contamination in the Hanover area; 5 to 8 million m^3 of sewage were found to be contaminating the aquifer in areas where the sewers lie permanently or temporarily above the water table. High sulphate concentrations were found in the groundwater in those areas where sewage entered the aquifer. In addition, boron and chlorinated solvents were detected, and nitrate levels were elevated. Toussaint (1989) also points to sewers as a source of chlorinated solvent pollution.

Schleyer *et al.* (1992) state that the full extent of the potential hazard confronting groundwater in Germany from leaking sewers was recognised only recently. They estimate that 10 to 15% of the 285 000 km of public sewers and 600 000 km of private sewers in the former West Germany have exceeded their life expectancy. They also estimate that approximately 300 million m^3 of waste water seeps into groundwater each year.

SITUATION IN IRELAND

As mentioned in the introduction to this paper, little has been written about sewer-related groundwater contamination in Ireland. The major exception is the much publicised incident at Naas in 1991, where leakage from a sewer contaminated a well, and led to some 4 000 cases of gastro-enteritis (Garrett, 1992). The source of the incident at Naas was a borehole known as Sunday's Well, located in what is now a housing estate bearing the same name. The borehole exploits Quaternary Sand and Gravel deposits. Problems with the Sunday's Well source commenced on 7 October 1991 with a consumer's complaint of a foul smell from the water after it was boiled. These complaints escalated and when the borehole was examined it was obvious that it had become contaminated by sewage. Initial water analyses showed presumptive coliforms in the order of 10^9 per ml and *E. coli* in the order of 10^7 per 100 ml. The contamination was traced to a blockage that had occurred in a sewer next to the borehole with consequent seepage of sewage into the borehole.

The supply was apparently chlorinated but this appears to have failed to deal with such gross pollution. Furthermore, super-chlorination of the source and mains only completely remediated the situation some two weeks after the original pollution incident.

The Naas incident illustrates the widespread and relatively immediate effects sewage-related groundwater pollution can have on public health. There was widespread local public concern and anger at the pollution incident. The local Environmental Health Department was besieged with queries ranging from '*can AIDS be contracted from the water?*' to '*was the water safe to bathe in for people who had undergone surgery?*'.

CONCLUSIONS

Sewer-related groundwater contamination is not uncommon, incidents having being reported in many countries. The majority of incidents reported did not lead to any ill-effect on public health, owing to adequate chlorination of water supplies. However, where contamination by sewage has coincided with inadequate chlorination (or none at all), the effects on public health have been dramatic (such as at Bramham and Naas).

Even where public health is not at significant risk, leaking sewers still constitute a pollution source with the potential to contravene groundwater quality regulations. Therefore, groundwater should be protected against the risks of contamination from sewers. This has been recognised by the National Rivers Authority (NRA) in England and Wales through the inclusion in its *Policy and practice for the protection of groundwater* (NRA, 1992) of the following policy statement:

> *'The presence of sewage works and the associated sewerage system present a risk of both bacteriological and chemical contamination to groundwater sources. The NRA would object to the creation of new works within both Source Protection Zones I and II. It would also oppose the laying of new main sewerage systems within Zone I, although the use of pipework which is less vulnerable to leakage would be considered on a case by case basis.'*

Sewers and sewer condition are thus very important issues in Source Protection Zone I and, to a lesser extent, in Zone II (Zones I and II are defined, respectively, by a 50-day and 400-day travel time from any point below the watertable to the source). However, the issues are more widely applicable. For example, leaking sewers are a potential concern where they are located on any aquifer outcrop, since they may pollute groundwater with a variety of contaminants from nitrate through to trade effluent species such as heavy metals and organic compounds.

Guidelines on groundwater protection in Ireland are currently being prepared by the Geological Survey of Ireland (Daly, 1994). The guidelines comprise two main elements, a land surface zoning map, which encompasses the hydrogeological elements of risk, and a code of practice for potentially polluting activities. Both elements are combined in a matrix type approach.

Based on the international experience of sewer-related groundwater contamination described in this paper, the authors feel it is important that the risks to groundwater quality from sewers should be evaluated in Ireland, and that sewers should be considered in any code of practice on potentially polluting activities. Prevention of groundwater contamination from sewage is clearly important for the sustainable development of groundwater resources.

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Table 1 Selected sewer-related groundwater contamination literature referred to in paper

Location	Nature of study/incident	Contaminants	Reference
England: Castle Springs, Bath	Leaking sewer in 1928 affected well in Jurassic Lst aquifer, and led to typhoid outbreak affecting about 50 people, 7 deaths	Bacteria	Halliday and Lerner, (1992)
England: Bramham, Yorkshire	Blocked sewer in 1980 affected PWS borehole in Magnesian Lst aquifer, and led to gastro-enteritis outbreak affecting 3 000 people	E. Coli, presumptive coliforms	Short (1988)
USA: Michigan	General contamination study with two examples cited of leaking sanitary and municipal sewers having contaminated wells, leading in one case to public ill health	Bacteria	Deutsch (1963)
USA: Castle Air Force Base, California	Study of groundwater contamination at Air Force Base. Leaky sewer pipes identified as a pathway for trichloroethene to have contaminated a shallow groundwater system over a 15 year period.	Trichloroethene	Avon and Bredehoeft (1989)
Germany	Two papers pointing out the connection between leaking sewers and groundwater pollution in Germany.	Not known	Hornef (1983, 1985)
Germany: Munich - Harlaching	Study of effects of urbanisation on a shallow Quaternary aquifer. Using the ratio of boron concentrations in sewage and groundwater, it is estimated that the leakage rate of sewers is 2% or 62 $m^3/day/km^2$.	Phosphate, boron, total organic carbon, chloroform, trichloroethene, tetrachloroethene	Merkel *et al* (1988)
Germany: Hanover	Discussion of groundwater management in the urban area of Hanover, Germany. Leaking sewers were identified as a source of pollution.	Nitrate, sulphate, boron	Mull *et al.* (1992)
Germany: Hesse	Discussion of the sources of chlorinated solvents in groundwater. The author demonstrates by six examples from southern Hesse, that leaky sewer systems play an important part in such contamination.	Chlorinated solvents	Toussaint (1989)
Germany	Discussion of wellhead protection zones in Germany. Identify leaking sewers as a hazard confronting groundwater quality.	Not applicable	Schleyer *et al* (1992)
Ireland: Naas	Sewage contamination of well in 1991, possibly affecting the health of 4 000 people.	Bacteria	Garrett (1992)

Figure 1 Incidents Identified for England and Wales from Various Sources

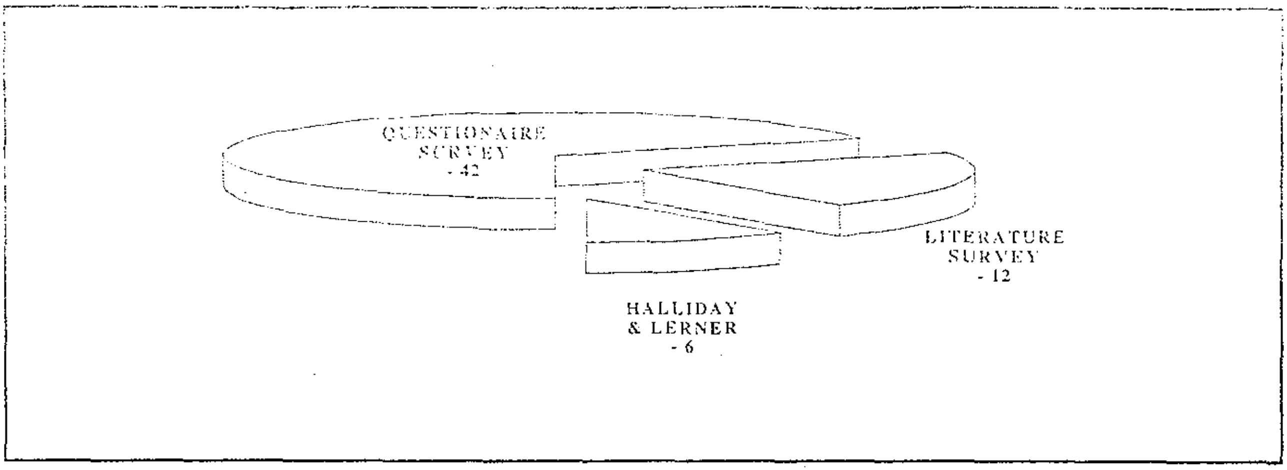


Figure 2 Number of Incidents Identified from Questionnaire Responses from Target Group

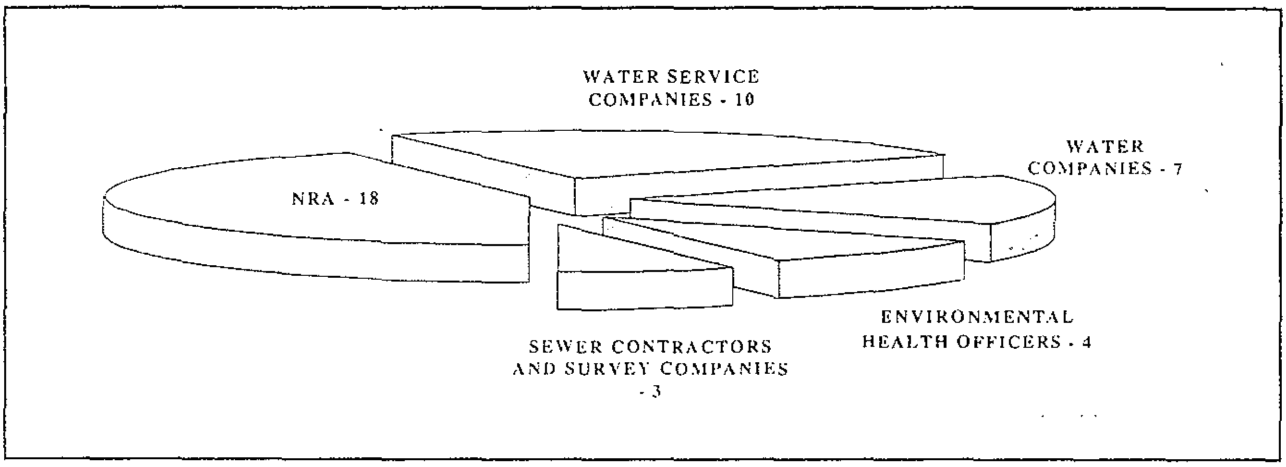


Figure 3 Breakdown of Incidents by Aquifer

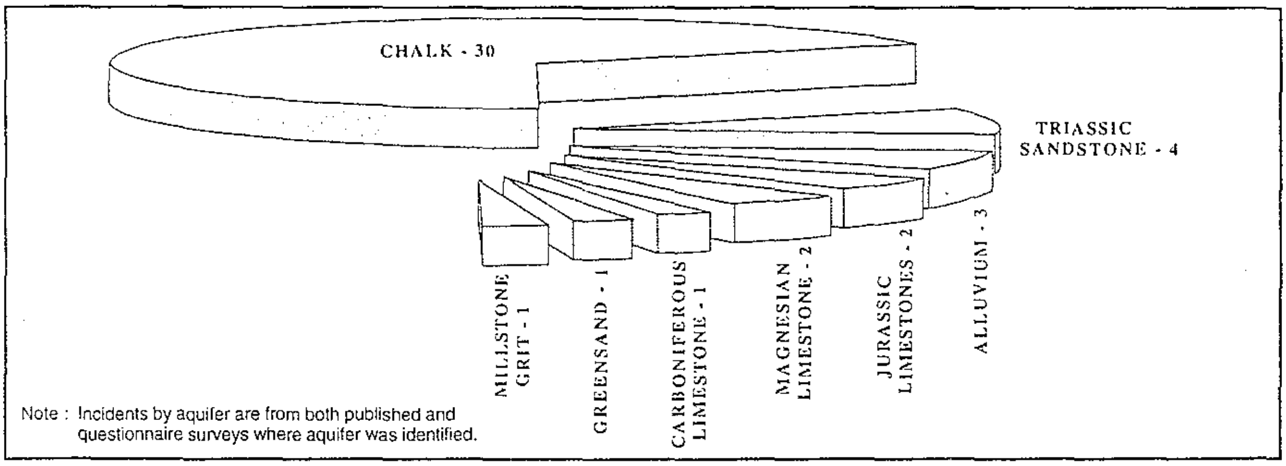
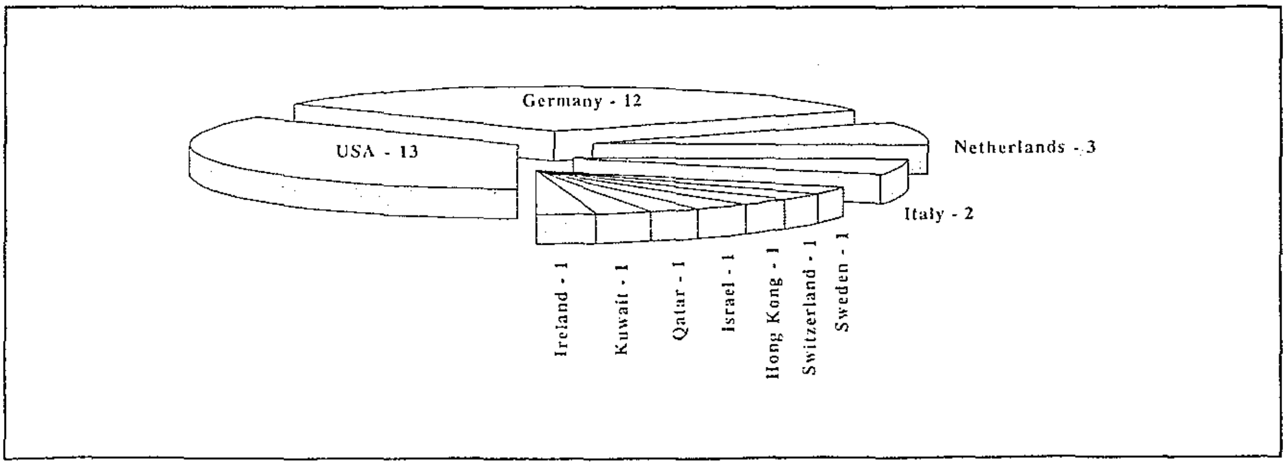


Figure 4 Published International Studies on Sewer - Related Groundwater Contamination



SUSTAINABLE GROUNDWATER SOURCES
A CONTRIBUTION TO AN IRISH NATIONAL BOREHOLE DRILLING STANDARD FOR WATER SUPPLIES - METHODS OF APPROACH AND PRACTICAL CONSIDERATIONS

David M. Ball
Hydrogeologist

ABSTRACT
There is a need for a change of perception, approach and attention to detail in the planning, construction, monitoring and management of a groundwater source. It is time for a wider understanding that a source is the combination of a resource, a structure and the monitoring and management of both resource and structure. These components of a source require detailed attention if the source is to be sustained. Equal emphasis should be placed on sustaining quality and yield. Making borehole yield a design priority may be misplaced in the long term and requires revision.

1. INTRODUCTION

The word source is a very useful word because its meaning is not restricted to just a borehole or spring. A prime purpose of this paper is to encourage the concept of a source in the full sense, and encourage an appreciation of all the care required to understand, create and sustain a good quality, reliable source. A second purpose of the paper is to try and blow away some of the cobwebs of past perceptions surrounding a borehole or well. Wells and boreholes are often described by their depth, without any acknowledgement of the method of construction, their integrity or proven sustainability. I think it is important to stress that a borehole or a well is just a hole in the ground. It is merely a construction that can allow access to the groundwater resource. Without the resource a hole in the ground has little intrinsic value. I think the pendulum of perceptions should be pushed away from the notion that a deep hole is somehow better than a less deep hole. It is the design and construction that is important. I think the same should apply to the notion of yield. The emphasis should be on the combination of sustainable yield and sustainable quality. I think we try to get too much out of our boreholes. A 20,000 gallons an hour borehole that is vulnerable to sudden changes in quality is a nightmare to manage in the long term, as many of the group water schemes and industrial users find to their cost. Several well designed, carefully constructed boreholes, with lower yields and reliable quality will provide a better, sustainable and economic source.

A third objective is to make a contribution to a future National Standard for Drilling Boreholes for Water Supply in Ireland. There is GSI Information Circulars 79/1and 85/1 on water wells and pumping tests and a code of good practice for borehole design and construction in NSAI IS432:92 The Irish Bottled Water Standard, but I believe we now need a comprehensive Irish Standard to cover all water supply boreholes. There is neither the time nor space in these proceedings to present such a standard. The points raised in this paper are just a contribution to the standard with an emphasis on concepts and details that will help sustain a groundwater source.

2. DEFINITION OF A GROUNDWATER SOURCE

A groundwater source is made up of three essential, linked components namely:-

1. The groundwater resource drawn upon by a borehole or well, or discharging freely at a spring.
2. The natural or, more probably, artificial structure used to draw upon the groundwater resource.
3. The protocols or procedures that must be carried out to monitor and manage both the resource and the structure drawing upon the resource.

It is well known that groundwater varies in terms of availability and quality with both the seasonal changes in the hydrological year and also the seasonal or periodic changes in man's activities at the surface. What is less well recognised is that long term or progressive changes can also take place in an aquifer and in the borehole itself.

An example of the former natural changes would be a rise in the water table as a result of autumn recharge. This could be accompanied by an improvement in yield or well efficiency because the saturated thickness of the aquifer has effectively increased. It could also be accompanied by a deterioration in bacterial quality because a pulse of soil bacteria is flushed by recharge down into the aquifer.

An example of the seasonal or periodic change induced artificially could be inappropriate landspreading of slurry or offal at a time of groundwater recharge.

An example of the long term or progressive change in the aquifer or borehole could be a growth of

bacteria as a biofilm on the surface of discharge pipes, the build up of encrustation on the slots in well screen or the progressive upwelling of saline or different chemistry water from deeper in the aquifer.
It is necessary therefore to understand the groundwater resource, design and construct an structure which can appropriately draw upon the resource, and carry out monitoring and management of the resource and the structure in order to obtain a sustainable groundwater source. A sustainable source implies that the source gives a yield and quality that is appropriate to the demands placed upon it and does not undermine the integrity of adjacent sources or other sensitive features. A groundwater source that has been proved to be sustainable is a valuable asset.
The objective of the following sections is to go through each of these components of a sustainable source, highlighting various factors I have found important from experience. Less emphasis will be placed on the resource aspects because this have been dealt with by Eugene Daly's paper.

3. THE GROUNDWATER RESOURCE

3.1. Well Inventory

It is essential to make an assessment of the groundwater resource before designing and constructing a sustainable groundwater source. It is prudent to do this before work commences on the new source. Favourable results from the assessment of the resource will give valuable information and also give confidence to proceed with the capital investment in a new source.
The first step is to carry out an inventory of existing boreholes, wells springs and relevant groundwater features. This can be partly achieved by gathering and assessing existing records. However it is better to undertake this work as a field survey.
The first decision is to define the extent of the well inventory field survey. Whilst all boreholes wells and springs around the site of the new groundwater source are relevant it must be stressed that the most important area is the groundwater catchment up gradient of the proposed source. Groundwater moves naturally from and under this catchment to the site, therefore conditions in the catchment area above the source control the quality of the water reaching the site. The well inventory should therefore place emphasis on obtaining information from the existing sources in this area.
A field survey is valuable for the qualitative and often anecdotal information obtained from existing sources and their owners. For example observations on taste or iron staining on taps can alert the hydrogeologist to a potential corrosion problem. This can be checked by the use of field pH and Eh equipment.
Similarly owners can often give information on changes in quantity and quality in summer or winter.
A well inventory should be carried out by a hydrogeologist. Standard field equipment would be a six inch scale map, water level sounding line, stop watch, EC meter, thermometer, pH and Eh electrodes and meter, sample bottles for water chemistry and bacteriology and a camera. Skill, experience and common sense is required to gain access to the boreholes and use the equipment to obtain reliable information on the groundwater resource that will ultimately sustain a new source down gradient.

3.2. Contamination Hazard Survey

Donal Daly and William Warren produced the GSI Guidelines on Mapping Groundwater Vulnerability to Pollution in the Groundwater Newsletter in July 1994. I use the term Contamination Hazard Survey to describe the other side of the coin. In the past this survey might have been called a 'land use survey'.
The objective of a contamination hazard survey is to assess the activities that take place, or may take place from time to time, in the catchment area that may influence the sustainable quality of the water from a new source. Though useful information can be obtained from aerial photographs, maps, records in the planning department or local Department of Agriculture offices, it is again best to carry out this survey on the ground. The hydrogeologist carrying out the survey is a little like a detective, observing the obvious but also following up on things that are less obvious. For example a perfectly clean modern building with nicely landscaped grounds could turn out to be a light industrial plant that assembles circuit boards and uses solvents for cleaning the boards before connections are made. Where do the solvents go after use? Where are the solvents stored? What happens in reality if a drum of solvent is spilt, does it get washed into a rainwater drain that terminates in a soakaway on top of the aquifer? Many of these activities are obviously relevant when they become known, but it is a sense of enquiry and persistence that is important in a contamination hazard survey
There are some contamination hazards that will not be evident during a survey. For example county council herbicide spraying along roadside verges, or periodic burying of carcasses or land injection of offal on farmland. Similarly it is important to acknowledge the risk of accidents on roads, particularly if the roads are used by bulk liquid carriers such as milk or fuel. An important consideration are buried fuel tanks or unbunded surface fuel tanks. These could be in industrial premises, agricultural Co-ops or at filling stations. Experience has shown that it is prudent to assume the tanks or connections leak until it is shown otherwise.
A contamination hazard survey can be carried out at the same time as a well inventory. It is easy to become alarmed at the number of contamination hazards even in the most idyllic rural setting. A groundwater catchment up gradient of a potential groundwater site that does not contain some

contamination hazard is very rare. It is therefore important to rank the risks in terms of severity and duration of impact and distance from the potential groundwater source and vulnerability of the aquifer. The combination of the results of the well inventory and the contamination hazard survey will yield information that has a bearing on the design of the new groundwater source and on the design of the catchment monitoring protocols to be carried out after the source has been constructed. The two surveys above could be regarded as baseline surveys.

4. BOREHOLE

4.1. Location

The location of a new groundwater source is often constrained by the site of the developer. Even so there are some obvious and less than obvious considerations that are worth expressing.

First it is important to consider vulnerability to both contamination from outside and inside the site and from vandalism. An ideal location from the external perspective would be a site as far as possible down gradient from adjacent lands upon which activities cannot be controlled and away from public roads or footpaths. Boreholes can be protected but it is wise to not make them obvious from the outside.

The ideal down gradient site will obviously have to be modified if either an existing plant or occupied building is on the site or if a new building is going to be constructed. The risks posed by an existing building can be assessed. The risks in the construction of a new building need careful thought and preparation. Modern building techniques involve the use of machines and many additives, solvents, mastics, wood preservers and paints. If a new source has to be sited down gradient of a new building it is important to ensure that all plant (diggers, graders, compressors, generators etc.) are refuelled off site in an area where fuel can be stored and spillages can be contained. Similarly whilst the correct application of paint probably poses little risk to groundwater the disposal of paint solvents wood preservatives etc. on the site adjacent to the borehole could have immediate and long term consequences. It is recommended that the hydrogeologist is involved in the supervision and environmental safety decisions for any new construction on a site upgradient or adjacent to a new high quality groundwater source.

There are numerous obvious considerations in terms of milking parlours, silage pits slurry pits, soakaways, septic tanks, sewers and fuel tanks that have been mentioned frequently in previous proceedings and are well expressed in the GSI guidelines on aquifer and source protection zones.

4.2. Borehole Design

The final design of a new production borehole should be preceded by the construction of at least one test or exploration borehole. This borehole might be considered as a trial that could be converted into a production hole but often this multiple objective leads to unacceptable compromises in the construction of the production hole. It is therefore best to drill an exploration borehole as an exploration hole and not try to achieve too much.

The purpose of the exploration hole is to establish the site groundwater conditions; the geology, permeability, chemistry and bacteriology. A the first hole on a new site could be likened to a voyage of discovery. The hole should be drilled under the direction and supervision of a hydrogeologist. The exploration hole should be constructed in such a manner that it can be tested with confidence for yield and quality, and used for long term groundwater monitoring.

The design of the production hole is based on the results of all the preceding work.

There is a considerable body of international literature concerning the design of a borehole or well. Some of it focuses on specific aspects in great detail. I cannot in the space available cover the whole area therefore I will restrict myself to comments and guidelines that may be useful in the context of local borehole design and drilling.

In Ireland there are two types of borehole design; first a simple borehole often designed by a driller within the financial constraints imposed by the client, and second a more sophisticated borehole designed by hydrogeologists and engineers for specific requirements. We cannot do much in the short term to improve or change the design of the typical cheap individual water supply borehole for a farm or house without a National Standard, but I think we can make immediate improvements in the design and construction of the professional water supply borehole.

Many of the basics are well known but I would add the following where I think improvements or changes can be made:-

1. Drilling Diameters

The concept behind borehole drilling diameters and casing and screen sizes is a telescope. There are a series of step downs in these diameters to allow for ease of insertion of casing, injection of grout and then onward drilling and installation of screen. I suggest that hydrogeologists should specify drilling sizes that are one step bigger than is the minimum needed. This is to allow for unexpected drilling problems. It gives the flexibility to case off a problem and still achieve the final design diameter. For example a hole which needs a producing section or open hole diameter of approximately 6" would be frequently sized as follows:-

Drill 9⁵/8" from ground level to base of the overburden
Insert 8" conductor casing
Drill 7⁵/8" open hole into bedrock
Insert 6" ID casing
Drill 5⁷/8" open hole section

Whereas I would recommend the following:-

Drill 13³/8" from ground level to base of the overburden
Insert 10" conductor casing
Drill 9⁷/8" open hole into bedrock
Insert 6" ID casing
Drill 5⁷/8" open hole section

The advantage with this design is two fold. First it means that if a drilling problem occurs in the 9⁵/8" section then it can be cased off with 8" casing and drilling can continue at 7⁵/8". If there is no problem then the large annulus around the 6" casing means the casing can be easily installed and a good thickness of cement grout can be emplaced around the casing.

2. The Concept of a Pump Chamber Casing

In many Irish aquifers there is a zone of high permeability at the base of the overburden and the top of the bedrock. In order to benefit from the relatively high yield in this zone, the final casing is set to the top of the bedrock, it is not fully grouted in, and the pump is often suspended in the open hole section below the casing. There are many flaws in this design when considered within the context of a sustainable good quality groundwater source. To shift the pendulum away from this design I would promote the concept of a pump chamber casing.

Electric submersible or lineshaft turbine pumps should not be suspended in an open hole with unlined sides. There are four reasons for this:-

a).Unstable portions of the bedrock can fall off and down and trap the pump so that it cannot be withdrawn to be replaced or serviced. If the pump cannot be withdrawn it requires either over drilling down the outside of the rising main; a tricky and expensive procedure; or the hole has to be abandoned when the pump fails.

b). Electric submersible pumps have an electric motor below the pump impellers. Part of the reason for this is that it is assumed the pump will be in a pump chamber casing and the motor will be cooled by an up flow of water past the motor to the intake at the bottom of the impellers. If the flow is from above then the motor can remain in static water and not be consistently cooled.

c). If coarse and fine sediment comes down the hole to the impellers it will all be sucked into the impellers and cause wear on the impellers and pump bowls. If water comes into the borehole from below the pump, the effect of less turbulent flow and gravity will tend to let the coarser fractions settle out to the bottom of the hole.

d). Pumps should be installed with centralisers on the pump and rising main. These are to hold the pump in the centre of the hole and allow an even flow to the pump inlet, evenly cool the motor and stop the whole assembly thrashing around in the hole when the pump switches in or out. However centralisers are seldom used, and a common cause of pump failure is abrasion on the power cable caused by movement of, particularly hydradare, flexible rising main against sharp edges on the bedrock. Placing a pump in a smooth sided pump chamber casing lessens the risk of this happening.

A pump chamber casing is advocated in order to seal off the upper high permeability zone at the base of the overburden. This may seem self defeating, if the emphasis is on yield, but it is not in the context of a sustainable good quality borehole source. Experience under a wide range of conditions in Ireland has shown that the groundwater obtained from this zone is often contaminated or subject to periodic contamination. In the context of a good quality sustainable source we should ask 'Do we want this water?' I appreciate that there is a fear of not finding fractures or permeable rocks at greater depth. Also there is a fear that deeper fractures may be directly linked to the upper poor quality zone. Decisions concerning these risks have to be taken. Confidence in taking the risk can be gained from the results of the exploration borehole. Sometimes the end user or client needs to be faced with a some difficult options: for example a lower yielding hole with sustainable good quality water plus water saving measures to reduce demand may be acceptable and preferable to abundant water of uncertain or poor quality and many downstream problems of treatment and biofouling and frequent treatment adjustments.

3. Cement Grouting

The case for grouting is straight forward. Casing has to be smaller in diameter than the drill hole. Therefore around the casing is an annular space. Unless this is sealed, water and other fluids can flow

down the annulus and enter the producing section of the borehole. An open annulus becomes a by-pass to any natural protection afforded by the overburden or low permeability horizons above the producing zone. A good quality groundwater from the producing zone may become unsustainable because poor quality water or surface contaminants can be drawn into the borehole. The value of grouting the annulus has become better appreciated during the last 10 years, but still it appears to be seen as something awkward and special rather than routine or standard. Part of the problem is extra cost and time delays and partly the absence of equipment and tools to carry out the work.
Grouting the annulus around a casing is difficult. The casing seldom lies central in the hole, and sometimes soft or unstable material in the upper horizons slumps against the casing. As a result the annulus varies in width. It is not possible to pour in a cement, sand and cement, or bentonite grout from the surface and have confidence that the annulus is fully sealed. It is likely that bridging will occur and air or water will be trapped. There will be gaps or pockets with no grout and the seal will be incomplete. Grout must therefore be injected from the base of the casing and fill the annulus upwards from the bottom.
The method used to inject a grout and the nature and consistency of the grout are important design considerations. Grouting cannot be done as an afterthought.
There are essentially two methods of emplacing grout. One is to inject grout at the base of the annulus outside the casing via a tremi pipe. If this method is used then the annulus should be at least 2 inches wide; i.e. the drill diameter is 4" wider than the outer diameter of the casing. This is to safely accommodate the tremi pipe diameter and the wider couplings. The larger annulus gives rise to wider diameter and more expensive drilling and also slower emplacement of larger volumes of grout. There is also a danger that an ordinary cement grout with a specific gravity of 1.7 to 1.8 injected into a 30 - 50 metre long annulus will start to set before the grouting is complete.
A second method is to mix up a large volume of grout and inject it from inside the casing (either directly via the casing or the drill pipe) out around the base of the casing and up the annulus. This can be done by using a grout float shoe with a non return valve on the bottom of the casing. I personally prefer the second method because it is efficient but float shoes and high capacity cement mixing tanks and duplex injection pumps are not common pieces of equipment in Ireland.
Grouting is complete when the grout shows at full strength at the surface. Drilling should not re-commence until a cement grout has achieved near full strength. This is likely to take 48 hours, therefore it is useful to aim to carry out grouting on a Friday and start drilling again on a Monday.

4. Choice of Materials for Future Quality Assurance
It is important to specify the casing and screen diameters, wall thickness', slot size, slot design etc. for a borehole on the basis of hydraulic efficiency and the hydrogeological conditions. This is well known and I will not refer to it further.
Borehole materials also have a considerable bearing on the long term sustainable efficiency of the borehole and the quality of the water. This is less often considered at the design and contract specification stage.
It is important to choose materials that have sufficient strength that they do not deform with temperature, pressure and change in hole diameter. These are not common problems in Ireland but with longer holes and in particular longer casing with cement grouting there are risks of deformation in cheaper plastic casings, which mean that pumps cannot be installed to the design depth and surge blocks cannot be used at a later stage to mechanically clean the inside of a hole.
It is important to establish from the exploration borehole whether the ground water is corrosive and then choose appropriate materials for the production borehole. Corrosive water can obviously destroy mild steel casing and widen the slot size on steel screen. Corrosive water also means that iron can be stable in the ferrous state in the water, and the presence of ferrous ions will encourage the growth of ferrophyllic bacteria slime biofilms that clog screen slots and spall off into the discharge water. Mild steel casing and screen is not recommended in even mildly corrosive water because it provides a ready supply of ferrous iron and a good media for bacteria growth.
Several groups of bacteria find PVC and ABS suitable media for attachment and growth as biofilms. Naturally occurring soil coliform species and pseudomonads readily grow on these materials. They are difficult to eradicate and control once they have become established. Plastic and fibre glass casing can become scored during the drilling of the producing zone. Removing bacteria from these scratches is difficult by chemical and mechanical methods. Therefore to obtain a sustainable good quality groundwater it is important to consider the choice of inert, strong casing and well screen that can be safely and easily worked over, mechanically or chemically, at a later date. Materials such as stainless steel are initially expensive but are cost effective over a long maintenance period of a borehole.

5. Choice of Drilling Method and Specification of Drilling Contract.
There are many aspects of a drilling specification and contract that require attention. I draw attention to a few that have a bearing on the sustainability of the source.

a). Specification of hygiene and cleanliness of the drilling rig, drilling tools and drilling additives. It is prudent to avoid contamination of the ground by dirty drilling tools. The outside of the drill string may be scoured by cuttings but the inner surfaces may carry oil and bacteria. Many rigs also leak hydraulic fluid and the leaks themselves plus attached mud or worse can fall down into the hole or contaminate the ground around the hole. This is not a serious problem if both the driller and the hydrogeologist are aware, but I once visited a drilling site where a leaking rig lost several litres of hydraulic fluid down the outside of a conductor casing over a weekend before grouting. The casing had to be withdrawn, the borehole cleaned as far as possible and eventually backfilled and abandoned. Drilling additives such as lube oil injected into the airstream for down the hole hammers should be kept to a minimum and shut off when drilling is not in progress.

b).Choice of drilling method for overburden and bedrock drilling.
Most bedrock boreholes in Ireland are drilled using the down the hole hammer method. Whilst this is efficient and appropriate for the bedrock it has disadvantages when drilling in clays and at the top of the bedrock in unconsolidated gravels and broken ground.
Down the hole hammer bits are not designed for drilling through soft, compressible materials particularly in the unsaturated zone. The result is that the bit does not create small cuttings that can easily be cleared from the hole. Instead the it creates large wads of clay that tend to clog the hole behind the bit and drill collar. These heavy lumps can only be cleared by high air pressures and air volumes. Even so circulation is frequently lost and air, or air and water is forced sideways into the overburden. This tends to fracture or open up fractures in the overburden, and air bubbles often appear at the surface some distance from the rig. This improves the vertical permeability of the overburden i.e. it breeches the protective, insulating nature of the overburden.
To conserve the natural characteristics of the overburden drilling should be slow and carefully carried out using long toothed drag bits, clay cutters or soft formation rock roller tri-cones.

c). Verticality
A borehole is seldom perfectly straight or vertical. Most holes are gentle helixes. This does not matter as long as the casing and screen can be installed freely and the pump can hang vertically.
However too much down the hole weight, incorrect diameter stabilizers or inclined beds of different hardness strata can lead to dog legged holes, stepped offsets and loss of verticality.
The consequences are noticed beyond the obvious construction problems in the form of increased pump wear. A pump that should last 8 years can be worn out in 3 months by wear on the bearings and impellers caused by lack of verticality.
I recommend that the centre line of the pump chamber casing should for its full length be less than 1degree off vertical, measured from the centre of the casing at ground level. This is not difficult to achieve. It just requires care, equipment and awareness.

4.3. Borehole Construction and Testing
A new borehole for a sustainable groundwater source should be drilled under the direction and supervision of an experienced hydrogeologist. The objective is to carry out the contract, make decisions on site in relation to the findings during drilling and in particular ensure that no aspect of the work is likely to prejudice the integrity of the aquifer or borehole in the future.
The new production borehole requires thorough yield and quality testing. In addition to the standard testing procedure I would suggest that testing under mock production conditions is extended to establish the optimum sustainable yield and quality. I suggest that an emphasis is placed on establishing a detailed understanding of the link between quality and pumping regime. For example daily measurements of key well head chemistry parameters and frequent bacteria sampling may indicate a correlation between quality and discharge rate and duration. A recent example showed that at a continuous low discharge the blend of water from a borehole had a sodium level of 58 - 64 mg/l. If the borehole was pumped over a long period, intermittently at a high discharge, the sodium level remained at 32 - 35 mg/l.

4.4. Borehole Completion
The completion of a borehole is often ignored, or seen as an after thought. This attitude is symptomatic of the old perception that the hole in the ground is the important thing. The completion of the borehole is critically important in the context of a sustainable groundwater source. If the borehole is equipped with inappropriate pump, controls, switch gear, rising main, valves, meters, sample points, pressure release valves, discharge pipe to the end user, and well house, a perfectly good groundwater source will become unmanageable and unsustainable. When designing the completion of a borehole it is wise to always bear in mind that things are going to change, things will go wrong and work will have to take place to correct problems and maintain the borehole. The borehole completion design should be made on this basis.
Below are some relevant points :-
The well house or pump house has to be designed and constructed so that either shear legs or a rig can be positioned over the hole in order to remove the pump or work over the hole. The well house should

also protect the well head from both the elements and casual intruders, and should be dry and drained because it will contain electrical switch gear.

I personally favour a design with outside dimensions that are 5 metres long by 3 metres wide and 2 metres deep, that has a roof at ground level. In other words it is a buried well house. The advantage of the design is that it is visually unobtrusive and the pump can be removed and the hole worked over via detachable roof panels. The borehole should be close to one wall and at one end. The space on one side should be sufficient to allow the use of 24 inch pipe wrenches. Admixes in the mass concrete floor and in a 3 coat layer of sand and cement plaster on the walls will keep the house dry even with high water table conditions. The walls can be built with concrete blocks and if necessary topped out with a reinforced concrete beam cast insitu. A thick hard standing should be made adjacent to the well house on the side nearest the borehole so that a rig can work directly over the hole. The well house floor should have a slight slope and at the lower end there should be drainage to take water spilt during sampling or leakage from pipe connections and the operation of a pressure release valve. A sustainable borehole should not be sited in a place where the winter water table is within 3 metres of ground level.

The borehole should have a detachable lockable cap which allows the insertion of a water level indicator probe but is vermin proof.

The rising main, valves, and pipework to the end user should ideally be stainless steel. This is to inhibit the growth of biofilms and to permit the use of strong chlorine solutions in a strong alkali base to treat biofilms when they develop. The long term problems with materials mentioned in the context of casing and screen equally applies to the rising main and delivery pipe. I accept that often stainless steel is too costly and cheaper alternatives must be used. The purpose of this note is to draw attention to the fact that cheaper alternatives can lead to severe degradation of the water quality and serious on-going maintenance and management problems in the future. The client and the consultant need to be aware of this risk at the time decisions are made concerning the completion of the borehole.

The pipe work at the well head must have provision for sampling the discharge for bacteria and water chemistry and pumping to waste during routine yield testing and cleaning. The discharge to the testing outlet should be controllable from inside the well house but the end of the pipe should be a sufficient distance from the hole to inhibit recirculation to groundwater near the hole. The sample taps or bleed nipples should be flameable for sterilisation and detachable for cleaning.

It is an added but prudent expense to install a return line from either the end user or storage reservoir to allow sterilising solutions to be circulated back to the well head and either down the hole or up the delivery pipe for cleaning in place or CIP.

The overall dimensions of the well house are designed to accommodate the pipe work valves and connections and also allow the electrical controls to be at hand but distant from the places where water may splash.

There are many other details to provide but space does not permit. However one final point is the area around the well house. I recommend that a stock proof fence should be located 30 metres away around the hole, with a wide gate for heavy equipment. The ground inside the fence should be maintained without the use of herbicides or fertilisers. Any further fencing using wood should not be treated in situ with wood preservatives.

5. COMPLETE SOURCE MONITORING AND MANAGEMENT

The monitoring and management of a source is a simple concept that has many ramifications. It involves the monitoring and management of the borehole and whole delivery system to the end user, the monitoring of the resource that is drawn upon by the borehole, and the management, as far as possible, of the landuse and other activities in the groundwater catchment area.

5.1. Resource Monitoring and Management

Eugene Daly's paper earlier in these proceedings has covered the basic components of resource monitoring. From the perspective of sustaining a source the focus shifts to monitoring of activities in the catchment area that may influence or prejudice the availability, quality and economics of groundwater at the site. The scale of monitoring ranges from a whole catchment monitoring of natural events such as rainfall, streamflow and the fluctuations in groundwater levels down to particular attention to events or activities on adjacent sites up gradient of the borehole. There are numerous examples but to take two; a new borehole or well field on an adjacent site that may deplete the resource or distort the groundwater flow system; or a change of landuse involving the application of fertiliser or herbicides. The monitoring process involves regular walks over the immediate catchment area, and driving the full catchment, in order to observe changes that may influence the source. It also involves monitoring planning applications lodged with the local authorities.

Management is more difficult. It involves education of neighbours and local authorities about activities that may be unacceptable, or lodging objections to proposed developments that may be prejudicial. It also involves spotting unauthorised dumping or inappropriate waste disposal, and arranging a clean up. A final, and extreme management technique would be to install scavenger or injection wells upgradient of the production boreholes in order to actively cleanup or block the flow of contaminated groundwater. The same monitoring principles apply to all activities on the site.

5.2. Production Borehole Monitoring

The purpose of borehole monitoring is two fold. First it meets the need to be sure that the borehole is operating normally and that the water delivered to the end user is within quality protocols. Second it is to get time-series information on the performance of the borehole and the groundwater quality that will show seasonal or long term trends. It is proposed that for an important groundwater source a series of key indicator parameters are measured at least once a day if not continuously. These key indicator parameters could be on-line measurements of water levels, discharge rates and electrical conductivity. The latter being a good general indicator of sudden changes in groundwater chemistry.

Protocols should be drawn up for routine monitoring of other parameters chosen on the basis of experience and the quality of the water required by the end user. If possible these parameters should be measured at the site, or in a site laboratory.

5.3. Production Borehole Management

Borehole management consists of two activities. First the routine cleaning, repair and maintenance of the borehole and the pumping equipment and delivery lines. Second a response to the raw and interpreted monitoring information.

It is recommended that the source production schedule includes provision for each production borehole to be shut down for at least two weeks each year, in order to clean the borehole, sterilise the equipment, and carry out pumping tests to observe any changes in performance and aquifer characteristics. A two week shut down is needed because chemicals may be used, and it is important to allow time for tests and the results that confirm the hole is meeting specifications before the borehole is brought back into production.

The management in response to monitoring information depends upon the frequency and quality of the information and the history or experience with the borehole and the aquifer in the past. For example after a year of monitoring and management it may be possible to be proactive rather than responsive. It could be that at the end of each summer it was observed that there was an unacceptable shift in the hydrochemistry, that arose from the upconing of deeper groundwater. Such an event could be proactively countered by a reduction in pumping rates perhaps accompanied by switching in an additional standby source.

Responsive management may involve a temporary shut down over a weekend to counter a sudden build up of bacteria as biofilms in the rising main or delivery line that is undermining the microbiological water quality. It could involve altering the pumping rate and regime in order to minimise the downward leakage from an upper aquifer contaminated by a spill or a sudden increase in bacteria levels after recharge.

6. CONCLUSION

The points raised in this paper have been presented to emphasise the importance of considering a sustainable source as more than just a hole in the ground. A source can only be sustainable if it is monitored and, as far as possible, managed from recharge to discharge and the structure that is used to exploit the resource is carefully sited, designed and constructed. The ideal is to find a source that never changes. My experience of reality is that all sources change; some daily, some with the seasons and some progressively over a long time. To sustain a source it is important to understand and plan for these changes. To do otherwise leads to insecurity and failure of the source.