GSI Guidelines for Assessment and Mapping of Groundwater Vulnerability to Contamination

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Acknowledgements

The vulnerability concept has been developing in Ireland since the early 1990s. Much of the material in this document is an accumulation of all that we have learned in Groundwater Section over many years. Some of the text has been taken from previously written documents, and some of it summarises the results of two specific research projects which were carried out to further our understanding of vulnerability mapping (Lee, 1999 and Swartz, 1999). Discussions have been held with many different people, both nationally and internationally. While the contributions have been many, the following people are particularly thanked for their input:

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1 Introduction

Groundwater vulnerability assessments are an integral part of groundwater protection schemes (DoELG/EPA/GSI, 1999). Vulnerability maps provide user friendly geoscientific information on the properties of the geological materials between the ground surface and the underlying groundwater. They are used by a variety of people for different purposes including:

- Local authority planners to aid in the siting of potentially contaminating activities.
- The EPA in assessing IPC licences and landfill developments.
- Hydrogeological and environmental engineering consultants, and local authority engineers for a range of environmental projects such as recharge assessment, contaminant transport, road improvement schemes, and groundwater development for drinking water supply.

Vulnerability maps also have future potential for use in integrated catchment management plans, for developing nitrate vulnerable zones and in assisting local authorities in their obligations with regard to the phosphate regulations.

This document is intended to serve as a comprehensive guide to understanding and assessing vulnerability. It provides a background to the definitions and concepts behind vulnerability; outlines the general geological and hydrogeological factors dictating groundwater vulnerability while focussing on those which are specifically relevant to Irish conditions; describes methodologies for assessing vulnerability in the field and for producing vulnerability maps; and considers vulnerability in the context of a risk assessment process as part of a groundwater protection scheme.

The objectives of this report are as follows:

- To set out the concepts and framework behind vulnerability mapping in Ireland.
- To outline a standard, consistent methodology for assessing vulnerability in the field and for producing vulnerability maps.
- To provide information and advice to new Groundwater Section staff, and to others involved in vulnerability mapping.
- To improve the quality and defensibility of Groundwater Section work.

1.1 Objectives of vulnerability assessment

The overall aim of the vulnerability assessment process is to provide relevant information for land-use planning decisions, so that potentially polluting developments can be located and controlled in an environmentally acceptable way. The objectives, which are interrelated, are as follows:

- To indicate the degree of natural protection against contamination and therefore the likelihood of contamination.
- To provide an essential zoning component for the groundwater protection scheme in use in Ireland.
- To enable rapid and consistent decision-making by environmental managers.

- To help in providing a hierarchy of levels of risk and, in the process, assist in targeting and setting priorities for technical resources and investigations.
- To help comply with the water pollution legislation and with the sustainable development and precautionary principles.
- To provide useful information in designing monitoring networks.
- To assist in creating public awareness of groundwater and the susceptibility of groundwater to human activities.

Vulnerability categories can be applied on a site specific basis and also in regional mapping, although the techniques employed for each may be slightly different, depending on the data availability. Both aspects are considered in this document.

2 The Groundwater Vulnerability Concept: General Geological and Hydrogeological Aspects

2.1 Definition

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.

2.2 Vulnerability as a General Concept

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

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

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

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

2.3 Groundwater Vulnerability - A Component of Risk and Risk Management

2.3.1 Risk and risk assessment

Risk can be defined as the likelihood or expected frequency of a specified adverse consequence. Applied to groundwater, it expresses the likelihood of contamination arising from potentially polluting sources or activities (called the hazard). A hazard presents a risk when it is likely to affect something of value (the target, which in this case is groundwater). It is the combination of the probability of the hazard occurring and its consequences that is the basis of risk assessment.

$$RISK = PROBABILITY\ OF\ AN\ EVENT \times CONSEQUENTIAL\ DAMAGE$$

The groundwater protection scheme used in Ireland (DELG/EPA/GSI, 1999) is based on the concepts of groundwater contamination risk and risk management. Relating a groundwater protection scheme to these concepts allows consistent application of a protection policy and encourages a rigorous and systematic approach.

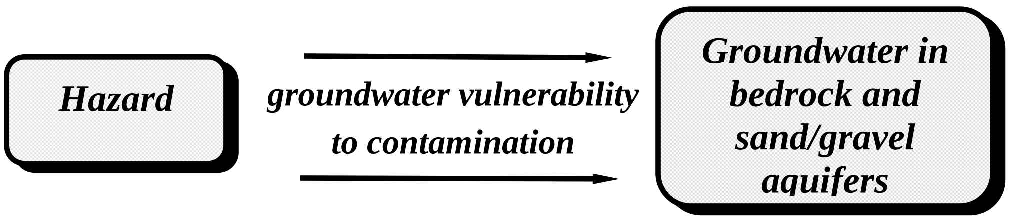
2.3.2 'Hazard-pathway-target'

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

Hazard: These are the developments and activities that pose a threat to groundwater. Key considerations are the type of contaminant, the contaminant loading, the potential hydraulic loading associated with the contaminant release, and potential the depth of release. The potential point of release of contaminants may be at the ground surface for activities such as landspreading of piggery slurry or 5 m below ground for developments such as storage tanks or landfills. It is a critical reference point for vulnerability assessment and mapping.

Target: The target (or receptor) is the water which has to be protected. Wells and groundwater dependent ecosystems are obviously potential targets, but in the Irish scheme the groundwater in the aquifer below a site is also a target in its own right. Note that the water in subsurface layers overlying the aquifer (e.g. tills and peat) is *not* normally a target. *Vulnerability assessments relate to groundwater in the uppermost bedrock or sand & gravel aquifer below a site.* This is a fundamental concept which underpins all the issues outlined in this document. Other targets that occur downgradient of the site (e.g. wells) are important considerations in the overall risk assessment, but are not considered by the vulnerability assessment *per se*. Descriptions of the risk to these downgradient targets that use vulnerability terminology are strongly discouraged.

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



The risk of contamination of groundwater depends on three elements:

(i) the hazard afforded by a potentially polluting activity;

(ii) the vulnerability of groundwater to contamination;

(iii) the potential consequences of a contamination event.

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

The hazard depends on the potential contaminant loading. The natural vulnerability of the groundwater dictates the likelihood of contamination if a contamination event occurs. The consequences depend on the value of the uppermost target, which is normally indicated by the aquifer category, and the proximity to downgradient targets such as a well or ecosystem. Preventive 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; etc. 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 include the vulnerability to contamination and the relative importance or value of the groundwater resource. The factors that relate to the potentially polluting activity are the contaminant loading and the preventive measures.

Risk to Groundwater

↙ ↘

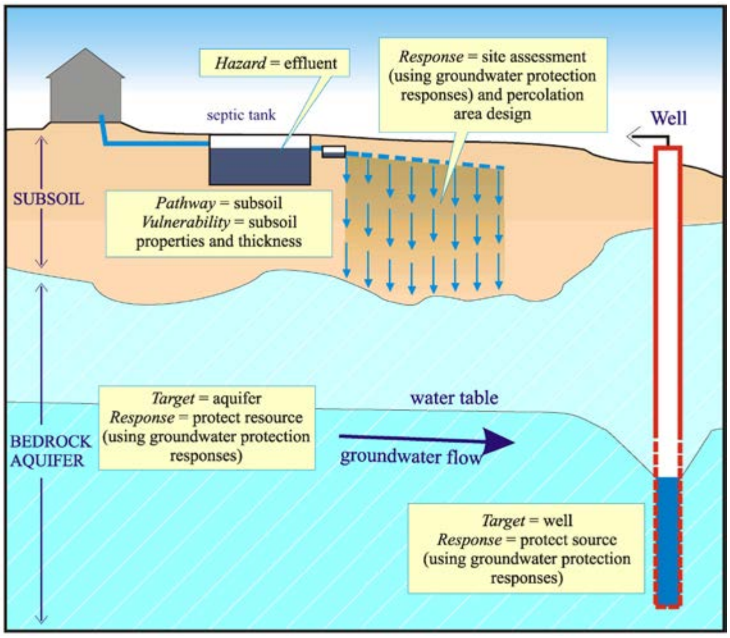
Hydrogeological Factors *Other Factors*

⇙ ⇘ ⇙ ⇘

Vulnerability to Contamination | Groundwater Value | Contaminant Loading | Response

A conceptual model of the relationship between these factors is given in Figure 2.1, where domestic wastewater effluent is taken as the hazard.

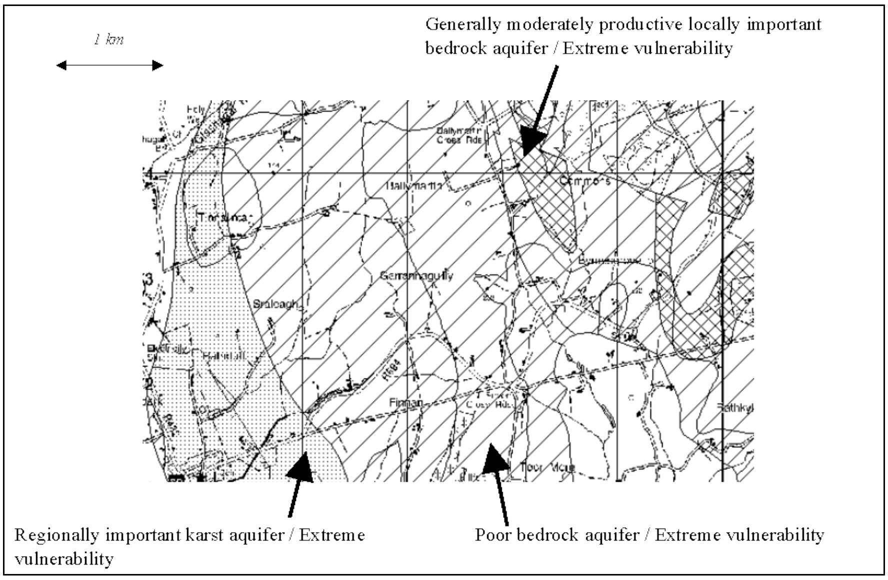
Figure 2.1 Schematic diagram showing how the elements of risk are applied to groundwater protection



It is important to stress that site suitability and the risk response measures do not depend on vulnerability alone. Figure 2.2 provides another example of the combination of two of the main elements (vulnerability and aquifer category) from an area of the Irish Midlands. If we are considering landfill site suitability (i.e. adding a hazard element to the risk assessment), the response measure in the three areas highlighted will vary. These are outlined in DELG/EPA/GSI (1999) and are available on the GSI website (www.gsi.ie). They are summarised as follows:

- *Poor aquifer / extreme vulnerability*: “Acceptable, subject to guidance in the EPA landfill Design Manual or conditions or a waste licence. Special attention should be given to checking for the presence of high permeability zones. If such zones are present then the landfill should only be allowed if it can be proven that the risk of leachate movement to these zones is insignificant. Special attention must be given to existing wells down-gradient of the site and to the projected future management of the aquifer.”
- *Generally moderately productive locally important bedrock aquifer / extreme vulnerability:* “Not generally acceptable unless it can be shown that; there is a minimum consistent thickness of 3m of low permeability subsoil present; there will be no significant impact on groundwater; and it is not practicable to find a site in a lower risk area.”
- *Regionally important karstic aquifer / extreme vulnerability: "Not acceptable”*. The responses go-on to recommend that exceptions can be made where the hydraulic gradient is upwards, in groundwater discharge areas, where site investigations do not find zones of significant permeability, or where the waste types are restricted.

Figure 2.2 An example of the combination of vulnerability and aquifer mapping



The key points to note from this example are:

- Though the vulnerability is mapped as being the same in all three areas, the response measures for landfill vary greatly. In this example, the variation is being driven by variations in the target rather than by variations in the pathway.
- A rating of extreme vulnerability does not necessarily preclude development, even for major developments like landfills.

2.3.3 The link between ‘vulnerability’ and the ‘pathway’

Vulnerability is based on evaluating the relevant hydrogeological characteristics of the geological materials along the pathway. Therefore it is assessed on the basis of the (largely) vertical transport of recharge water and contaminants from the point of release of contaminants to the uppermost groundwater target encountered, whether in a bedrock or sand & gravel aquifer (see Figure 2.3). This will be the water table, where the water table is in the bedrock or sand/gravel, or alternatively it will be the top of the bedrock or sand/gravel where the water table or potentiometric surface is in the overlying subsoil. It will not be the groundwater encountered in overlying subsoils, as this groundwater is not given a value as it is not used directly for water supply. Therefore, conditions along the pathway may be saturated or unsaturated or both.

2.3.4 Vulnerability and contaminant type

Relevant properties of the most common contaminants are described in Section 3. They have helped form the conceptual framework for identifying the four main vulnerability categories (refer to Section 4). However, when assessing vulnerability of groundwater below a particular area or site, the characteristics of individual contaminants are not taken into account. The vulnerability would be the same for a readily degradable compounds like certain pathogens or petroleum products as it would be for highly resistant compounds like nitrates and chlorinated solvents.

In other words, a vulnerability assessment will assume that the contaminants are conservative (i.e. they do not attenuate readily and move at a similar rate to water itself). The contaminant type and loading rate, along with vulnerability, targets, etc, are collated independently and the risk posed by a particular activity is then assessed by considering the elements together.

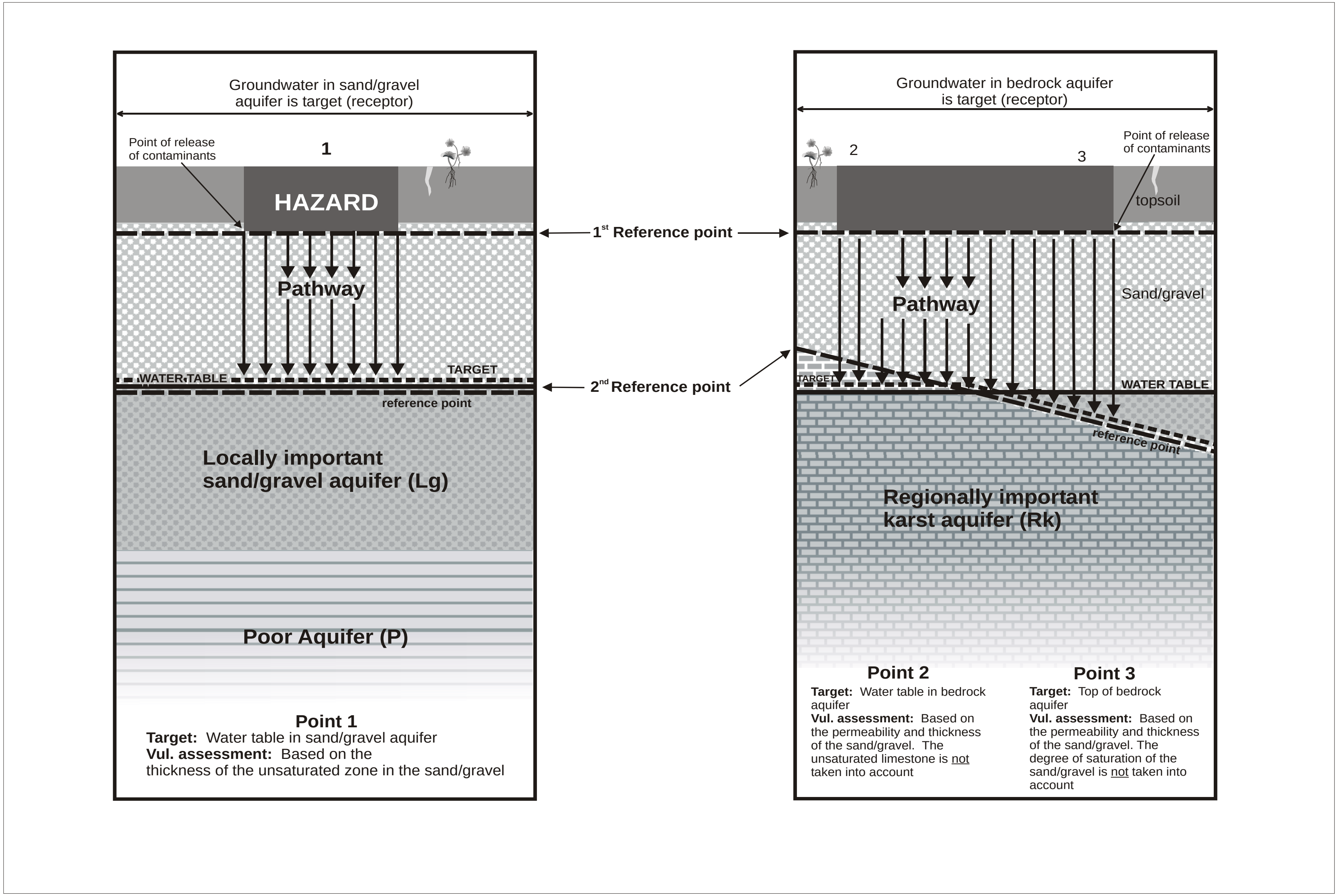


Figure 2.3: Illustration of the hazard-pathway-target concept and the hydrological factors that govern vulnerability assessments. The assessment is based on the relevant properties of the subsoil between the first and second reference

3 General Contaminant Attenuation Concepts

3.1 Introduction

There are three different types of processes that treat the main contaminant types that occur in Ireland:

- *physical processes*, including filtration, dispersion and dilution;
- *chemical processes*, involving cation exchange, adsorption and precipitation;
- *biological processes* consisting of biological oxidation, nitrification, denitrification, plant uptake, immobilisation, inactivation and predation.

Table 3.1 Contaminant attenuation in soils and subsoils – an example for domestic effluent

Process		Effect	Conditions
PHYSICAL PROCESSES	Filtration	Remove organic and mineral particulate matter and pathogens (mainly bacteria) in small voids	Unsaturated zone best; finer textured with moderate permeability most efficient
	Die-off	Many of the microbial contaminants are not viable in the subsurface environment.	Die-off increases at higher temperatures, lower moisture contents, where there is less sorption capacity, in acid soils, and where there is less organic matter.
	Sedimentation	Remove bacteria, some viruses, and particulates by settling out on soil and subsoil particles where quiescent zones exist.	More likely where flow through macropores and fissures are not extensive
	Dilution and dispersion	Reduces the concentration but not the overall mass of the contaminant	Most important for chemicals such as nitrate (NO_3) and chloride (Cl).
CHEMICAL PROCESSES	Cation exchange	Adsorption of cations onto negatively charged exchange sites on clay minerals and organic matter. Influences movement of K, Na, NH_4, Ca, Mg and metals.	Depends primarily on clay and organic matter content, and on pH.
	Adsorption	Weak binding, sometimes temporary, of metals, viruses and organic substances to surface of soil and subsoil particles.	Fine textured soils and subsoils with many fine voids show more adsorption. Unsaturated flow enhances adsorption. However organic substances and viruses can be 'rinsed out' to groundwater.
	Precipitation	Important for fixation of P.	Aerobic conditions and neutral or high pH enhance ppt
	Biological oxidation	Oxidation and breakdown of micro-organisms and organic compounds by other micro-organisms e.g. mineralisation of organic N to NH_4.	Nutrients and carbon source in biomat and aerobic conditions beneath mat enhance degradation.
BIOLOGICAL PROCESSES	Nitrification	Oxidation of NH_4 to NO3.	Requires aerobic conditions.
	Denitrification	Biological reduction of nitrate to nitrous oxide or nitrogen gas that escapes to the atmosphere.	Takes place only under anaerobic conditions with suitable carbon source.
	Predation	Decreases bacteria, protozoa and helminths.	Requires aerobic conditions
	Plant uptake	Decrease in nutrient content (N, P, K, Ca, S and Mg) of the effluent by plant absorption. Also removes water from the soil.	Requires that effluent is close to ground surface.
(Adapted from Arnold et al 1996)			

These processes depend on the subsurface ground conditions and the nature of the contaminants themselves. The key ground conditions are introduced in Section 4 and are the main focus of this document. Though vulnerability assessments are made independently of contaminant type (refer to Section 2.3.4), some of the concepts used to develop the assessment criteria are based on the properties of certain common contaminants. These properties are introduced briefly in Sections 3.2 to 3.4.

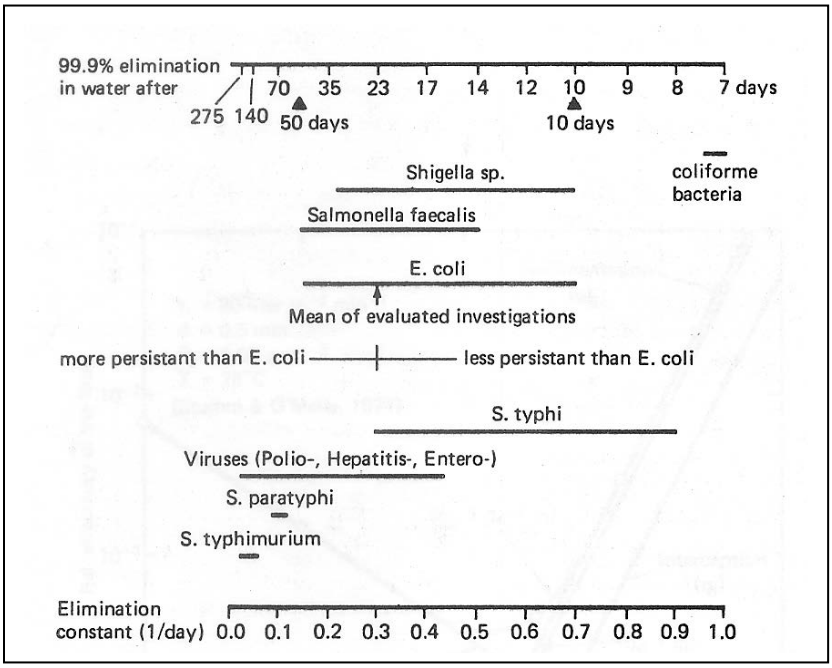
3.2 Faecal bacteria and viruses

E. coli is the parameter tested as an indicator of the presence of faecal bacteria and perhaps viruses; constituents which pose a significant risk to human health. The most common health problem arising from the presence of faecal bacteria in groundwater is diarrhoea, but typhoid fever, infectious hepatitis and gastrointestinal infections can also occur. Although E. coli bacteria are an excellent indicator of pollution, they can come from different sources – septic tank effluent, farmyard waste, landfill sites, birds. The faecal coliform:faecal streptococci ratio has been suggested as a tentative indicator to distinguish between animal and human waste sources. However, researchers in Virginia Tech (Reneau, 1996) cautioned against the use of this technique.

Viruses are a particular cause for concern as they survive longer in groundwater than indicator bacteria (Gerba and Bitton, 1984).

The published data on die-off of bacteria and viruses in groundwater has been compiled by Pekdeger and Matthess (1983), who show that in different investigations 99.9% elimination of E. coli occurred after 10-50 days (refer to Figure 3.1) The mean of the evaluated investigations was 25 days. They show that 99.9% elimination of various viruses occurred after 16-120 days, with a mean of 35 days for Polio-, Hepatitis-, and Enteroviruses. According to Armon and Kott (1994), pathogenic bacteria can survive for more than 10 days under adverse conditions and up to 100 days under favourable conditions; enteroviruses can survive from about 25 days up to 170 days in soils.

Figure 3.1 The time taken for elimination of some relevant bacteria and viruses in groundwater (after Pekdeger & Matthess, 1983)



Bacteria can move considerable distances in the subsurface, given the right conditions. In a sand and gravel aquifer, coliform bacteria were isolated 100 ft from the source 35 hours after the sewage was introduced (Hagedorn, 1983). They can travel several km in karstic aquifers. In Ireland, research at Sligo RTC involved examining in detail the impact of septic tank systems at three locations with different site conditions (Henry, 1990; summarised in Daly, Thorn and Henry, 1993). Piezometers were installed down-gradient; the distances of the furthest piezometers were 8 m, 10 m and 9.5 m, respectively. Unsurprisingly, high faecal bacteria counts were obtained in the piezometers at the two sites with soakage pits, one with limestone bedrock at a shallow depth where the highest count (max. 14 000 cfu's per 1000 ml) and the second where sand & gravel over limestone was present (max 3 000 cfu's per 100 ml). At the third site, a percolation area was installed at 1.0 m bgl; the subsoils between the percolation pipes and the fractured bedrock consisted of 1.5 m sandy loam over 3.5 m of poorly sorted gravel; the water table was 3.5 bgl. Yet, the maximum faecal coliform bacteria count was 300 cfu's per 100 ml. Faecal streptococci were present in all three piezometers. It is highly likely that wells located 30 m down gradient of the drainage fields would have been polluted by faecal bacteria.

As viruses are smaller than bacteria, they are not readily filtered out as effluent moves through the ground. The main means of attenuation is by adsorption on clay particles. Viruses can travel considerable distances underground; depths as great as 67 m and horizontal migrations as far as 400 m have been reported (as reported in US EPA, 1987). Note that indicator bacteria such faecal coliforms have been found not to correlate with the presence of viruses in groundwater samples (US EPA, 1987).

Clearly, survival times of microbial contaminants is variable depending on the loading, the nature of the subsurface and the type of microbe. In the absence of conclusive evidence, the balance of available studies suggests that significant die-off of most microbial contaminants will occur within 100 days' residence within the subsurface.

In addition to simple residence time, the natural environment, in particular the soils and subsoils, can be effective in removing bacteria and viruses by predation, filtration and absorption. There are two high risk situations: (i) where permeable sands and gravels with a shallow water table are present; and (ii) where fractured rock, particularly limestone, is present close to the ground surface. The presence of clayey gravels, tills, and peat will, in many instances, hinder the vertical migration of microbes, although preferential flow paths, such as cracks in clayey materials, can allow rapid movement and bypassing of the subsoil.

3.3 Nitrate and Ammonium

Nitrate is one of the most common contaminants identified in groundwater and increasing concentrations have been recorded in many developed countries. The consumption of nitrate rich water by young children may give rise to a condition known as methaemoglobinaemia (blue baby syndrome). The formation of carcinogenic nitrosamines is also a possible health hazard and epidemiological studies have indicated a positive correlation between nitrate consumption in drinking water and the incidence of gastric cancer. However, the correlation is not proven according to some experts (Wild and Cameron, 1980). The EC MAC for drinking water is 50mg/l.

Aside from gases, nitrogen (N) exists principally as two forms in the soil-water environment: organic (humus) and mineral (nitrate and ammonium). The organic form is generally considered immobile.

Ammonium can be held on the exchange complex of soils and is therefore not subject to leaching losses. Ammonium can also be fixed by expandable clay minerals. It has a low mobility in soil and subsoil and its presence at concentrations greater than 0.1 mg/l in groundwater indicates a nearby waste source and/or vulnerable conditions. Nitrate, on the other hand, is a conservative ion and is not adsorbed on clay or organic matter (Kolenbrander, 1975). It is highly mobile and, under wet conditions, is easily leached out of the rooting zone and through soil and permeable subsoil. As such, the compound is not readily attenuated in the hydrogeological environment.

Nitrate concentrations will be expressed in this document as concentrations of the ion, rather than as concentrations of the nitrogen component (‘nitrate-N’). A nitrate concentration of 50 mg/l is equivalent to 11.3 mg/l nitrate-N.

To understand nitrate in the environment, it is essential to understand the nitrogen (N) cycle. The aspects of this cycle in relation to ‘natural’ nitrate generation and loss can be divided into:

- *Internal transformations of N within the soil-plant system*; for example by the mineralisation of soil organic matter to nitrate in aerobic, oxidising conditions. The following formula is a simplification of the transformation of ammonium-N to nitrate-N:

  $$\underset{Ammonium}{NH_4^+} + \underset{oxygen}{2O_2} \rightarrow \underset{nitrate}{NO_3^-} + \underset{protons\ and\ water}{2H^+ + H_2O}$$

- *Additions of N to the soil-plant system*; for example by symbiotic fixation from legumes.
- *Losses of nitrate from the soil-plant system*; by direct removal of harvested crops or animals, by leaching to groundwater or by denitrification. Leaching to groundwater is often enhanced in the winter, because of the greater potential for soil water movement, and because of the absence of N uptake by dormant plants (Neill, 1989). Henry and Meneley (1993) note that, in soil systems where an abundant supply of nitrate is available, and where the soil moisture content exceeds field capacity at a time of year when the temperature is conducive to microbial growth, denitrification can be ‘very large and very rapid’. They go on to suggest that the soils most susceptible to denitrification have ‘clay and heavy clay textures’, and that bedrock aquifers overlain by more than 15m of this material can be classified as ‘Low Risk’ in terms of nitrate contamination in Western Canada. The following formula is a simplification of the process of denitrification by organic matter:

  $$\underset{organic\ carbon}{5CH_2O} + \underset{nitrate}{4NO_3^-} \rightarrow \underset{nitrogen\ gas}{2N_2} + \underset{bicarbonate,\ carbon\ dioxide\ and\ water}{4HCO_3^- + CO_2 + 3H_2O}$$

- *Losses from groundwater or surface water*; generally only by denitrification, though a decrease in nitrate concentration can also be caused by dilution processes such as groundwater recharge. The uptake of N by plant growth in surface water is limited by the concentration of phosphorus (Lucey et al, 1997). In groundwater, Appello and Postma (1994) note that substantial nitrate reduction requires the presence of reduction potential within the aquifer material. They go on to indicate that solid phases which could provide such potential in aquifers are organic matter, pyrite, and Fe(II) silicates. Denitrification by organic matter is described above. Nitrate reduction in aquifers has been reported when coupled with the oxidation of sulphur and Fe(II) from pyrite (Robertson and Cherry, 1992).

  The link between iron and denitrification in aquifers is supported by a number of studies, which have noted that high iron/manganese and high nitrate levels do not normally co-exist in soil or groundwater, even in areas with a high percentage of cultivated land (e.g. Croll and Hayes, 1988, and Robertson, 1979).

Sources of nitrate can obviously also come from human activities such as storage and spreading of agricultural wastes, spreading of inorganic fertilisers, urban centres, sewerage systems, and industry. Some examples are provided in Table 3.2.

Table 3.2 Common nitrate hazards in Ireland

	Point Hazards	Diffuse Hazards
Organic Sources	Sewage: • On-site wastewater treatment systems • Sewage lagoons • Leaky Sewers Farmyard: • Manures and slurries • Silage effluent • Dirty water Waste disposal sites. Contaminated surface water. Industry.	Organic wastes spread on land: • Manure • Slurry • Silage effluent, blood, etc • Sewage sludge, etc Soil organic matter. Urban areas (effectively an agglomeration of point sources).
Inorganic sources	Waste disposal sites Industry.	Inorganic fertilisers spread on land. Rainfall. Geological sources (e.g lignite, coal, peat)

As normal concentrations in uncontaminated groundwater are low (less than 5-10 mg/l), nitrate can be a good indicator of contamination by fertilizers and waste organic matter.

In the past there has been a tendency in Ireland to assume that the presence of high nitrates in well water indicated an impact by inorganic fertilizers. This assumption has frequently been wrong, as examination of other constituents in the water showed that organic wastes - usually farmyard waste, probably soiled water - were the source. The nitrate concentrations in wells with a low abstraction rate - domestic and farm wells - can readily be influenced by soiled water seeping underground in the vicinity of the farmyard or from the spraying of soiled water on adjoining land. Even domestic wastewater effluent can raise the nitrate levels; if a septic tank system is in the zone of contribution of a well, a four-fold dilution of the nitrogen in the effluent is needed to bring the concentration of nitrate below the EU MAC (assuming that the N concentration in septic tank effluent is 45 mg/l).

3.4 Phosphorus

Phosphorus is a significant contaminant and cause of eutrophication in surface water in Ireland. It is not generally a problem in groundwater and is not likely to be in the future. There are two reasons for this:

- Phosphate is strongly adsorbed onto positively charged particles and can react with many cations, particularly calcium, aluminium and iron, to produce relatively insoluble minerals (e.g. hydroxyapatite).
- The maximum admissible concentration for drinking water (5000 µg/l P_2O_5 = 2200 µg/l P) is rarely approached, except in areas of gross contamination.

However, in surface waters the concern with phosphorus is at much lower levels; total phosphorus concentrations in excess of only 20 µg/l P may trigger eutrophication in some lakes (Champ, 1998). Recent research in the Environmental Sciences Unit, TCD, has pointed out that in certain hydrogeological situations, the sorption capacity of the pathway can be exceeded and enhanced leaching to groundwater can occur. Kilroy (1999) studied groundwater monitoring data from Ireland and notes that “42% and 24% of the sites have mean orthophosphate-P levels greater than the adopted eutrophication thresholds for lakes and rivers, respectively”. Kilory also cites examples where leaching of P from soils has been identified in sandy soils with a high permeability, soils with a low P sorption capacity, and areas with shallow water tables.

In conclusion, P does not generally present a problem for groundwater. However, depending on conditions in the pathway, groundwater can provide the pathway for P to reach downgradient targets such as lakes, streams and wetlands.

4 Derivation of Vulnerability Assessment Criteria

4.1 Introduction

Before deriving the criteria, it is important to be clear on the purpose of vulnerability assessments.

The risk posed by a particular activity and the derivation of risk response measures are not dependent on vulnerability alone. The assessment also requires a consideration of the hazard, the uppermost groundwater target, and downgradient targets.

Potentially polluting activities can be divided into:

a) Major developments, which tend to have a high potential contaminant loading, an infrequent occurrence, and requirements for specific environmental impact considerations (e.g. landfill, factories, etc).

b) Minor developments which tend to have a lower potential loading, more frequent occurrence, and are generally handled under normal planning procedures (e.g. on-site domestic wastewater treatment systems).

For major developments, the concepts outlined in Section 2 (including vulnerability) are intended to provide a simple, scientifically defensible process for screening-out higher risk areas prior to specific works on short listed sites. Though the use of the concepts is encouraged throughout the process, planning decisions at specific sites can be based on more specific and elaborate risk assessment techniques. Issues such as the attenuation of specific contaminants, vertical hydraulic gradients, and layered subsoil sequences can become key considerations that are assessed using detailed analytical and modelling techniques. Results of these assessments may not affect the vulnerability rating of the site *per se*, but will have a critical influence on the site suitability assessment as a whole.

For minor developments, the use of the risk assessment tools outlined in Section 2 will be more important. Site investigation will be required for all sites, and may be specific to specific activities (e.g. percolation tests for on-site domestic wastewater treatment systems). However, in contrast to major developments, the thrust of the investigation and planning issues are more likely to focus on establishing the appropriate vulnerability category for the site.

In summary:

- Vulnerability is not the only factor in assessing the risk to groundwater quality.
- All developments require site investigation to assess the actual conditions within the pathway overlying the target.
- Issues surrounding the more major developments may well use vulnerability terminology, but the risk assessment procedures will often use more elaborate concepts in addition to those outlined in this document.

In this context, the vulnerability categories outlined in this document do not have to account for every hydrogeological scenario in Ireland. Given the use to which vulnerability assessments will be put, and given that backup information will be provided by site-specific investigations, it is more important for the vulnerability categories to account for the most typical Irish conditions. The vulnerability assessment criteria identified in this document are based on simple calculations which, in turn, are based on reasonable assumptions from a broad knowledge of conditions in Irish pathway materials. In some sites, the criteria will be over-restrictive, while in others they will be over-restrictive. The onus is on the developer to identify exceptions.

4.2 Attributes determining vulnerability

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

- *Travel time*: This relates to the residence times of infiltrating water and contaminants within the pathway:
  - The more rapidly contaminants can reach groundwater, the shorter the time interval available to deal with a pollution incident.
  - Certain contaminants (e.g. microbes from animal gut) are unstable in the subsurface environment and degrade over time. The longer the time spent within the pathway, the more these contaminants will degrade.
- *Quantity*: In areas where the hydraulic loading of contaminated waters is insignificant compared to that of natural potential recharge, this factor will relate closely to the recharge acceptance characteristics of an area. As discussed in Section 4.4, recharge acceptance relates to the proportion of *potential* recharge that can become *actual* recharge. Most contaminants reach groundwater dissolved within soil waters that have infiltrated from surface. A proportion of waters potentially available for recharge will usually be diverted laterally away from groundwater by restrictions within the unsaturated zone. The higher proportion of water that is diverted, the lower the loading of contaminants will be to groundwater.
- *Attenuation*: The contaminant attenuation capacity of the geological materials along the pathway. Contaminants are attenuated within the subsurface. The rate of attenuation will vary depending on both the type of contaminant and the nature of the subsoil materials. However, it is generally the case that clays and organic materials will provide higher levels of attenuation for most contaminants.

Table 4.1 Summary of key attributes determining groundwater vulnerability

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

In essence, all groundwater is hydrologically connected to the land surface and the effectiveness of this connection determines the relative vulnerability to contamination. Groundwater that readily and quickly receives water (and contaminants) from the land surface is more vulnerable than groundwater that receives water (and contaminants) more slowly and in lower quantities.

Table 4.2 Conceptual link between groundwater vulnerability and the attributes of the pathway

		Extreme	High	Moderate	Low
Attributes of the pathway influencing vulnerability	Travel time through pathway	<100 days	Months-years	Several years	>10 years
	Quantity of water and contaminants that can reach groundwater	Variable	Variable	Variable	Less than one fifth
	Contaminants where significant attenuation expected	Variable, depending on the pathway.	Microbial (excluding certain viruses) and many organic contaminants.	Microbial (including viruses), most organic & most inorganic contaminants	Most contaminants, including nitrate.

The attributes determining vulnerability can be assessed through 2 core elements:

1. 'Type of recharge' (point or diffuse). This is termed 'flow concentration' in the European Approach (COST Action 620) and 'infiltration conditions' in the German PI method (Goldscheider et al., 2000). It expresses the degree to which the protection provided by the geological materials (or overlying layers) is bypassed. This element takes account of karst areas where there is point recharge at swallow holes, collapse features, etc, with rapid flow to groundwater, bypassing of the soils and subsoils and minimal attenuation before groundwater (the target) is reached.
2. The protection provided by the geological materials/layers within the pathway overlying the target. Key factors are;
   - The porosity/permeability characteristics of the pathway.
   - The thickness of the unsaturated zone through which the contaminant moves.
   - The permeability and thickness of the subsoils within the pathway.
   - The presence of bypass flow mechanisms within the soils

The remainder of Section 4 comprises a discussion of each of these elements in the context of travel time, quantity and attenuation capacity.

4.3 The Role of Porosity/Permeability Type

4.3.1 Porosity

Porosity is the ratio of openings (voids or pore spaces) to the total volume of subsoil or bedrock. Porosity is usually expressed as a percentage of the bulk volume of the material. A noticeable feature of the porosity values in Table 4.3 is the marked contrast between the subsoils and bedrock. In subsoils, the voids or openings were formed at the same time as the rock; they give a 'primary porosity'. Openings that were formed at a later stage give a 'secondary porosity'(refer to Figure 4.1).

Figure 4.2 illustrates how a well sorted gravel has a significantly greater porosity than one that is poorly sorted.

Table 4.3 Typical porosity ranges

Subsoil	n(%)	Bedrock	n%
Topsoil	50-55	Limestone	0.5-5
Clay	30-60	Sandstone	0.5-5
Silt	30-50	Granite	0.1-5
Well sorted sand/gravel	25-40		
Sand & Gravel mixes	10-30		
Till (boulder clay)	10-30		
Undrained peat	>85		

Figure 4.1 Porosity and permeability types in subsoil and bedrock

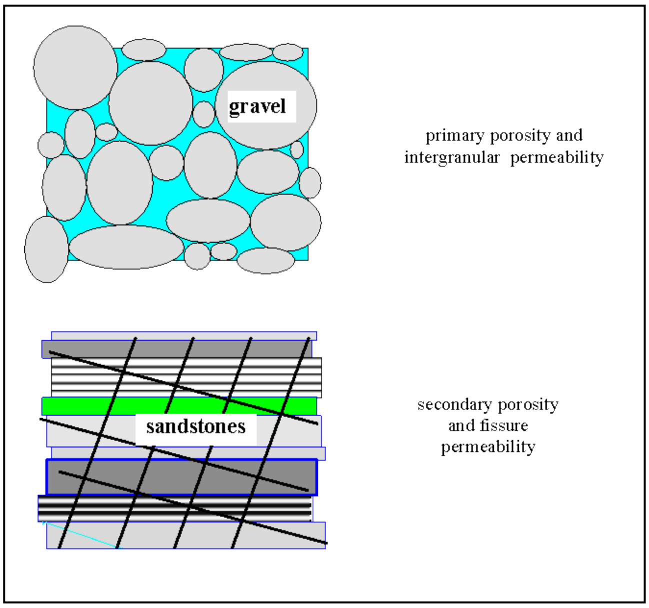
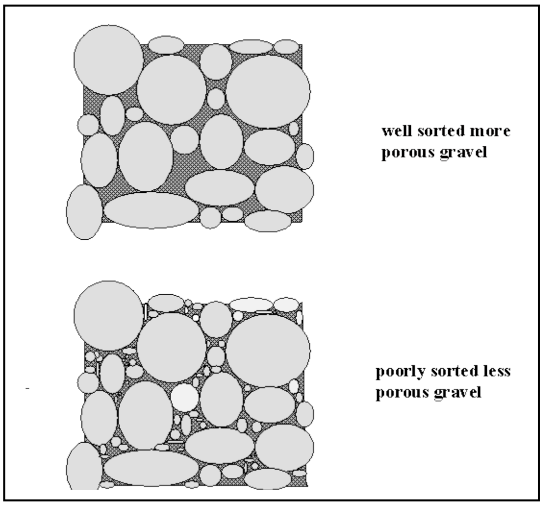


Figure 4.2 Porosity variation in gravel



4.3.2 Permeability Characteristics

Hydraulic conductivity or permeability, in qualitative terms, is a measure of the capacity of a rock to transmit water. It depends on the size and arrangement of the water transmitting openings (pores and fissures). Geological materials which allow water to pass through them easily are said to be ‘permeable’; those which allow water to pass only with difficulty, or not at all, are ‘poorly permeable’. The commonly used units by hydrogeologists are m/d and m/s. The term "permeability" is often loosely used instead of hydraulic conductivity and it will be used for the remainder of this report.

Permeabilities in Irish subsurface materials vary across a wide range, but levels below 1 m/day would generally be considered ‘moderate’ to ‘low’ while those above 10 m/day would generally be considered ‘high’. There are two distinct types of permeability:

- *Intergranular permeability*: the water moves between the grains of subsoils such as glacial till and sand & gravel, it is called primary or;
- *Fissure permeability*: the water moves through fractures or fissures or joints and along bedding planes.

Intergranular permeability:

This type of permeability is generally only significant in materials with significant primary porosity. In Ireland, these comprise the soils and subsoils. The permeability of these materials depends on the grain size and the degree of sorting during the sedimentation process. The first factor is self evident - the larger the grain size, the easier it is for water to pass through the pores and therefore the higher the permeability. Consequently, sand and gravel have a higher permeability than silty or clayey till (boulder clay).

The degree of sorting is also important; as depicted in

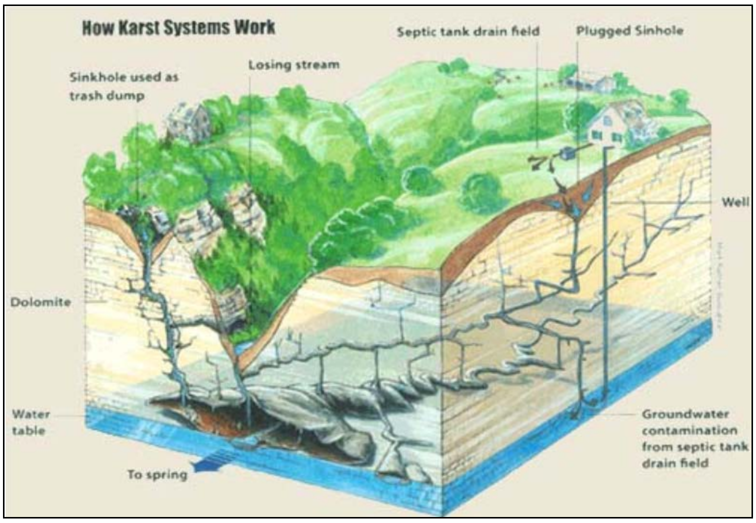
Figure 4.2, a well sorted gravel (gravel with a small range in grain size) has a higher permeability (and porosity) than one that is poorly sorted (having a large range in grain size). In the poorly sorted situation, the finer grains infill the voids between the grains making flow more difficult.

Fissure permeability:

In the Republic of Ireland, the bedrock aquifers are not thought to exhibit significant intergranular permeability. Fissure permeability is considered dominant.

Figure 4.3 provides an example of how fissures might appear within the overall mass of rock. Note that this is an extreme example: fissures in most aquifers will be more frequent and smaller.

Figure 4.3 Fissure permeability in a highly karstified aquifer



4.3.3 Subsurface flow

In saturated porous media flow rates can often be estimated using Darcy's Law, where:

Velocity = permeability × hydraulic gradient ÷ effective porosity

Flow = permeability × area × hydraulic gradient

Permeability can be variable in both primary and secondary porosity situations. However, porosity is generally much lower in fissured rock than in subsoil materials (refer to Section 4.3.1). As a consequence, intergranular flow is generally slower than fissure flow under most conditions. In addition, porous material will result in more irregular flow pathways on a small scale and will generally cause greater hydrodynamic dispersion of contaminants, which will tend to reduced their concentration in any one locality.

4.3.4 Summary of porosity/permeability characteristics

There is generally far greater degradation and purification of pollutants in subsoils with an intergranular permeability than in rocks with a fissure permeability:

- In contrast to rocks in which fissure flow dominates, the slow flow rate in subsoils with an intergranular permeability delays the entry of pollutants into groundwater and, particularly in the unsaturated zone, allows time and opportunities for interactions between pollutants and rock grains.
- The relatively small pore sizes within a porous matrix allow filtration and absorption of bacteria and viruses.
- The irregular flow paths within a porous matrix causes hydrodynamic dispersion which decreases pollutant concentration. For contaminants that reach the water table and enter groundwater, dilution is much greater in rocks with an intergranular permeability and thus the resultant contaminant concentrations are much less.

The worst situation is in karst limestone areas where flow rates are very high - over 100m/hr in some instances. There is little scope for attenuation other than by somewhat limited dilution.

In summary, once water reaches the Irish bedrock aquifers, there will be very little opportunity for attenuation, even in the unsaturated zone. The type of bedrock aquifer or the thickness of the unsaturated zone therefore does not form part of the vulnerability assessment.

Table 4.4 Comparison of the attributes of porosity/permeability than relate to groundwater vulnerability

	Primary porosity and intergranular permeability	Secondary porosity and fissure permeability
Travel time	Often long	Often very rapid
Quantity of water & contaminants	Variable	Variable
Attenuation capacity	Potentially good	Generally only die-off in slower flowing situations

4.4 Recharge type

4.4.1 Introduction

Groundwater recharge may be defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir' (Lerner *et al*. 1990).

There are two main types of recharge: diffuse (vertical infiltration of precipitation where it falls on the ground) and point (infiltration following runoff). It is generally acknowledged that in temperate climates most recharge is diffuse, whereas in arid regions most recharge occurs from surface runoff. However, this relation between climate and dominant recharge type does not always hold true: there are some situations in temperate regions where indirect recharge dominates, most notably in karst areas (where recharge occurs from losing rivers and via swallow holes and other solution features).

4.4.2 Diffuse Recharge

The estimation of diffuse recharge can be a complex process involving considerations of climate, aquifer properties, the properties of overlying soil/subsoil, vegetation, and topography. Most estimations begin with a consideration of 'potential recharge', which is thought to represent the excess of rainfall over evapotranspiration at times when the there is no deficit of soil moisture (i.e. when the soil is at 'field capacity'). At other times, the excess rainfall is first used to replenish the soil moisture store. Potential recharge can therefore be regarded as 'excess soil moisture available for recharge or surface water runoff' and is a function largely of climate and vegetation. Some workers do not include rapid storm runoff in the estimation of potential recharge.

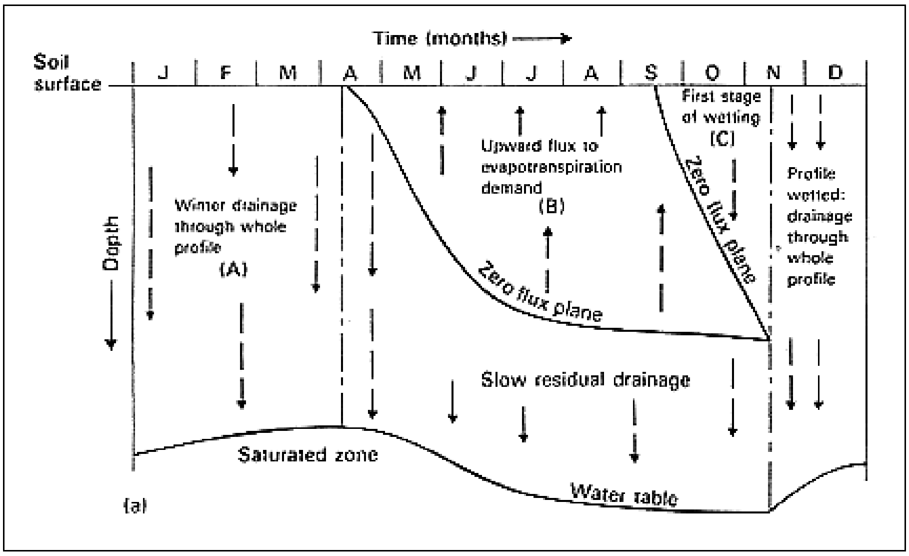
Figure 4.4 Estimated average potential recharge (moisture excess) in mm/year After Daly, 1995 and Collins et. al, 1986.

Rainfall in Ireland is generally high (typically 800 to 1200 mm/year) compared to evapotranspiration (typically 400 to 500 mm/year). Both parameters are distributed spatially and over time:

- *Spatial distribution*: Lowlands and the east receive less rainfall than uplands and the west, while evapotranspiration is higher along the coast than inland.
- *Seasonal distribution*: Using Met Eireann data from Kilkenny City for the period from 1994 to 1998, it is estimated that slightly more than half (60%) annual rainfall occurs in the winter and autumn, while only one fifth (20%) of the annual evapotranspiration occurs in these seasons. As a consequence, up to 80% of the estimated potential recharge at Kilkenny is thought to occur in the autumn and winter. This effect is described in Figure 4.5 and field evidence is provided in Figure 4.6 where the hydrographs demonstrate generally rising water levels (indicating recharge exceeds discharge) between late September and early March, and generally falling levels for the remainder of the year. Note that the hydrographs in Figure 4.6 do demonstrate *occasional* rising water levels in the summer months (e.g mid-1997). This is attributed to short periods of heavy summer rain which can temporarily eliminate the soil moisture deficit or which can trigger bypass flow mechanisms. *Downwards* bypass flows can occur in certain isolated soil features (refer to Section 4.7) even when there is a soil moisture deficit and when net soil water movement is *upwards* across most of the soil profile. Rushton & Ward (1979) modelled summer bypass flows whenever daily rainfall exceeded 5 mm.

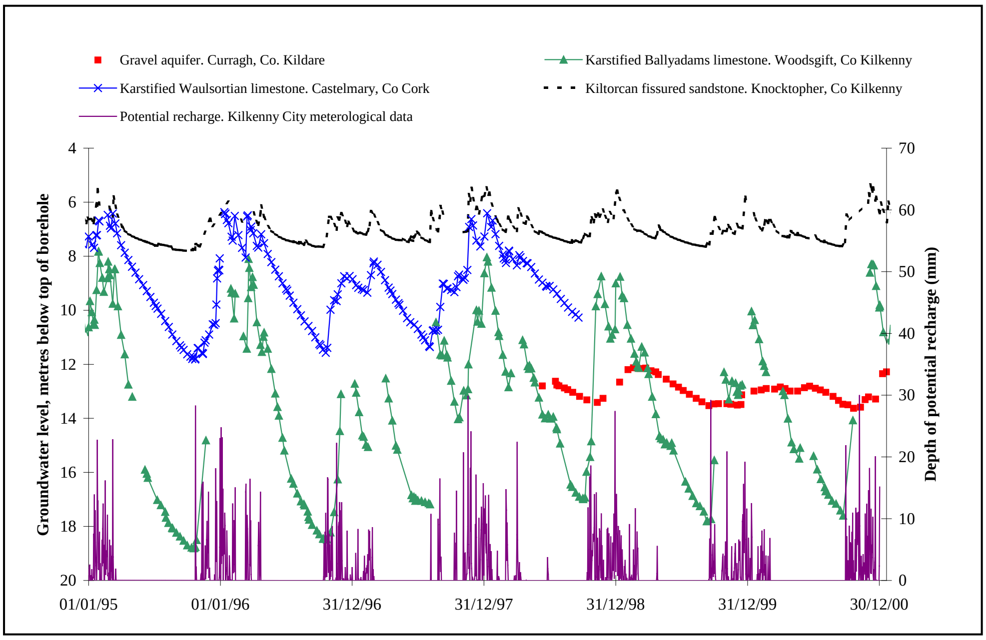
The number of days over the period from October to March when the soil moisture deficit was less than 5 mm comprised 88% of the whole period, suggesting that soils are usually at field capacity over this period. The average annual potential recharge was estimated to be 500 mm/year. Given that recharge occurs mostly in the autumn and winter, the average daily recharge is estimated to be in the order of 3 mm/day.

Figure 4.5 Annual cycle of water movement in a soil profile in a temperate climate (after Ward & Robinson, 1990)



In summary, potential recharge in Ireland is generally quite high annually, is concentrated in the winter months and is higher in the west than in the east. Average annual rates are in the order of 400 mm to 800 mm/year moving from east to west across the most populated areas of the country (refer to Figure 4.4). Though most recharge will occur in winter, some summer recharge can occur during and after periods of heavy rain. The amount of summer recharge will generally be insignificant in terms of water resource calculations, but it can be significant in terms of contaminant transport.

Figure 4.6 Selected Irish fissured and sand & gravel aquifers and their response to recharge



Diffuse recharge occurs across the entire national territory. As a simplification, waters from successive recharge events can be envisaged as moving downwards as series of 'pistons' through the subsoil during the later autumn, winter and early spring (refer to Figure 4.5). Each 'piston' pushes the older waters further downwards and brings with it contaminants released at surface from diffuse hazards (e.g. spreading of sewerage sludges) or released at depth from point hazards (e.g. percolation areas from domestic wastewater treatment systems). The concept of 'piston flow' means that rising groundwater levels can be observed very soon after a suitable storm event at surface, but the contaminants associated with the storm event may not reach the water table for some time. Piston flow is a simplification which is often disrupted by spatial and temporal variations in recharge and subsoil material, but it has been observed by field experimentation. Diamond and Shanley (1998), for example, measured soil water tensions (unsaturated pore water pressure) at a variety of depths in a clay loam soil. They noted that "with the onset of rain at the end of September the soil wetted from the surface downwards, and … the tensions in the surface … were lower than in the underlying material ..[but as potential recharge continued into the winter the deeper levels became wetter] ..the moisture profile reverted to the pattern that obtained in winter and spring with moisture tensions decreasing with depth."

The rate of recharge is therefore closely related to the rate of contaminant movement through the pathway, particularly for the conservative contaminants and where the hydraulic loading of contaminated water is not significant (refer to Section 2.3.4).

'Actual' groundwater recharge may be considerably smaller than the amounts suggested in Figure 4.4; generally in the order of tens to a few hundreds of millimetres per year. This is partly because a significant proportion of waters infiltrating below the soil zone will be diverted laterally by lower permeability restrictions within the subsoils overlying the aquifer and will not reach the water table within the aquifer. 'Recharge acceptance' relates to the proportion of *potential* recharge that can became *actual* recharge.

Some estimates of recharge acceptance rates for different subsoil materials are presented in Section 4.6.3. Taking one example from an important aquifer in the east of Ireland, the area might receive 400 mm/year *potential* recharge, but where it is overlain by generally thick, low permeability till, the average *actual* recharge might be as little as 20 mm/year.

It is clear that subsoil materials can have a significant influence on the *quantity* of potential recharge and contaminants that actually reaches the water table.

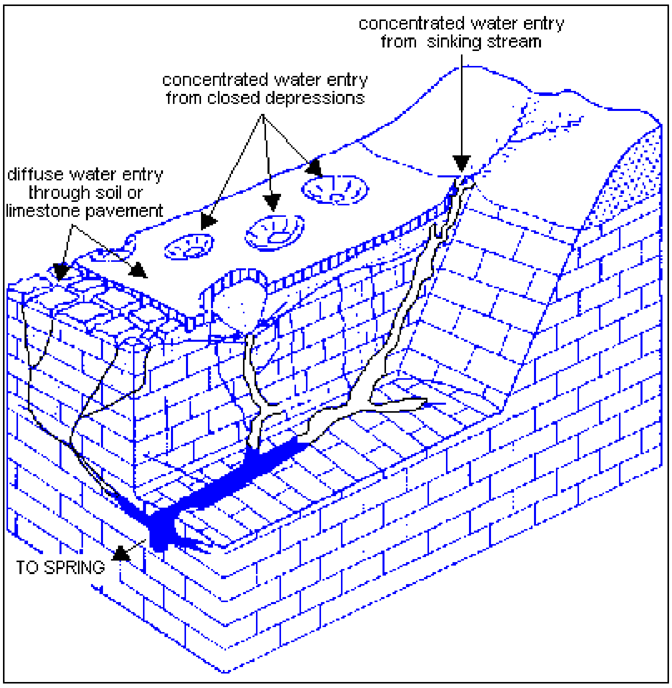
In addition, though localised variations will occur, infiltrating water and contaminants will generally move as intergranular flow through the pore spaces within the subsoil materials that comprise the pathway. Consequently, the *travel time*, and contaminant *attenuation* are also closely related to the rate of potential recharge, the thickness of the unsaturated zone, and the nature of the subsoils overlying the groundwater target. This aspect is discussed further in Sections 4.5 and 4.6.

4.4.3 Point Recharge

In certain situations, groundwater can be recharged at isolated 'points' rather than across broad, diffuse fronts. In Ireland, this occurs within karst features such as swallow holes, sinking karst streams, and dolines.

In contrast to diffuse recharge, infiltration relating to point recharge does not occur through the pore spaces within the subsoil materials overlying an aquifer. Consequently, the travel time and quantity of contaminants and attenuation capacity are unrelated the nature of the subsoils overlying the groundwater target. In most cases, therefore, the travel time will be rapid, the recharge acceptance will be high, and the attenuation will be minimal. Therefore, groundwater is at its most vulnerable close to these point recharge features.

Figure 4.7 Schematic of point and diffuse recharge mechanisms in a karst system (courtesy John Gunn, XXX)



4.4.4 Implications of recharge characteristics

A good understanding of the recharge mechanisms in an area is fundamental to the assessment of groundwater vulnerability. Where point recharge can occur, the vulnerability of the groundwater target is at a maximum. Where diffuse recharge occurs, vulnerability is controlled by the porosity and permeability of the subsoils that comprise the pathway, by the saturation conditions and by the possibility of bypass flows. These factors are discussed in Sections 4.5 to 4.6 below.

Table 4.5 Comparison of the attributes of recharge that relate to groundwater vulnerability

	Diffuse Recharge	Point recharge at karst features
Travel time	Variable	Very rapid
Quantity of water and contaminants	Variable	Very little will be diverted laterally away from groundwater
Attenuation capacity	Potentially good	Virtually none

4.5 The thickness of the unsaturated zone in Sand & Gravel Aquifers

4.5.1 Introduction

The unsaturated zone has the following beneficial effects on contaminants:

- contaminants have to travel farther to reach groundwater;
- flow rates are slower than in the saturated zone;
- attenuation is higher.

Thicker unsaturated zones will therefore generally reduce the vulnerability of groundwater, but only in permeable materials where intergranular flow is dominant. This is because:

- The unsaturated zone is most likely to develop to significant thicknesses in the permeable soils and subsoils. Diamond and Shanley (1998) studied three soils at three sites in South East Ireland. They noted that the most clay-rich soil (a well drained clay loam) remained saturated for 136 days at 1.2m depth in 1997 , while the coarsest soil (well drained sandy loam) remained saturated at 1.2m depth for only 32 days.
- The unsaturated zone will be most effective at attenuating contaminants where the permeability is sufficiently high to allow water to move through it freely. As a consequence, the nature of the unsaturated zone in a low permeability material (e.g. a clay) has little relevance to vulnerability assessments.
- The unsaturated zone in Irish bedrock aquifers has little beneficial effect (refer to Section 4.3).

In essence, the unsaturated zone will be most effective at attenuating contaminants where it can develop to greater thicknesses and where the permeability is sufficiently high to allow water to move through it freely. In Ireland, this combination of conditions applies where sand & gravel aquifers are at surface.

4.5.2 Travel time in the unsaturated zone of sand & gravel aquifers

As described in Section 4.2, the key limits of this attribute are 100 days, several years and more than 10 years.

Travel time in unsaturated material is governed by equations similar to Darcy's law (described in Section 4.3.3). However, velocities can often be much slower than their equivalents in saturated material. This is primarily because effective permeabilities in the unsaturated zone are often several orders of magnitude lower. In addition, velocities are also more variable than in the saturated zone because flow rates, permeability, pressure gradients and moisture contents are all strongly inter-dependent.

However, some broad assumptions can sometimes be made when considering typical flow over a long time period across a wide area. Mulqueen et al (1999) suggest, "the results of many field experiments show that long term leaching of solutes through many field soils can be modelled with average water flow rates and average pore water contents (Charbeneau and Daniel, 1993). Using only simple advection theory, i.e. neglecting dispersion, .. net recharge [q]… and average pore water content [θ] .. the pore water velocity (v) can be computed from $v = q/\theta$ …"

In winter time, recharge can be considered as the key driver of unsaturated zone flow processes and the moisture content, hydraulic gradients and permeabilities will adjust, if possible, to accommodate the recharge. In lower permeability materials, even the saturated permeability will often be insufficient to accommodate all the potential recharge this approximation will become less applicable.

As discussed in Section 4.4, average recharge rates in the winter are in the order of 3 mm/day at Kilkenny and the soil is predicted to be at or just below field capacity for almost 90% of the late autumn-early spring period. Average moisture contents are difficult to obtain as they are variable laterally, with depth, with recharge rate, and with material. During instantaneous profile testing on free draining soils, Mulqueen et al (1999) identified volumetric moisture contents ranging from ~ 10% to ~25% at depths below 1m. Dunne et al (1975), as reported in Ward and Robinson (1990), suggest that most soils (including sands) have field capacities in excess of approximately 10%. If we assume that the average moisture content throughout the winter months is close to field capacity within the unsaturated zone, that the moisture content at field capacity will rarely be less than 10% and that the recharge is typically 3 mm/day over this period, a winter-time velocity of up to 0.03 m/day can be estimated.

Note that these estimations comprise an approximation of the typical rate of flow across a wide area of unsaturated, highly permeable, intergranular material. Slower flow rates will occur in areas of greater saturation. More significantly, much higher velocities can occur in areas of locally higher recharge, or where bypass flow mechanisms are operating. Richards (1999), for example, undertook bromide tracer experiments in the top 1.5m of sandy soil material at a farm and found flow rates ranging from to 0.01 to 0.06 m/day, depending on the location and whether the first tracer arrival or the peak concentration was used to estimate velocity. Richards went on to cite another worker who claimed to have identified bypass flow after finding tracer at 1.5 m depth within 17 hours of application (2 m/day average velocity).

Assuming that most bypass flow occurs within the *soil* horizons (refer to Section 4.7) and that the estimate of 0.03 m/day is broadly representative of unsaturated *subsoil* flows, a travel time of 100 days would require and unsaturated subsoil thicknesses of 3m. Travel times of more than, say, 3 to 4 years and more than 10 years would require unsaturated subsoil thicknesses of 35 m and 110 m, respectively. Unsaturated sand & gravels of this thickness are very rare in Ireland.

4.5.3 Quantity of water penetrating the unsaturated zone of sand & gravel aquifers

As described in Section 4.2, the key limits of this attribute is 20% potential recharge acceptance.

It is assumed that recharge acceptance is significantly greater than 20% in all sand & gravel aquifers except where the water table is very close to surface (e.g. in discharge zones) and/or where they are overlain by lower permeability subsoils.

4.5.4 Attenuation capacity in the unsaturated zone of sand & gravel aquifers

The unsaturated zone provides an aerobic environment, where the most rapid treatment of effluent occurs. Oxygen allows aerobic bacteria and other micro-organisms to feed on the wastewater and break down the contaminants to simpler and less harmful products. Aerobic conditions promote rapid die-off of some pathogenic bacteria that require anaerobic conditions to live and favour the growth of aerobic bacteria which feed on anaerobic populations (Arnold et al. 1996). They also aid chemical processes such as precipitation by maintaining a neutral or alkaline pH.

In unsaturated sands & gravels, the combination of an aerobic environment and relative slow flow rates provides an opportunity for die-off of bacteria and viruses and for the various beneficial chemical and biological processes to attenuate the contaminants.

Clearly, thicker unsaturated zones will be more effective because the surface area available for attenuation will be greater and because travel times will generally be slower.

4.5.5 Implications for vulnerability assessments of sand & gravel aquifers

The unsaturated zone thickness will only be a significant factor where the target is groundwater within a sand & gravel aquifer.

Though travel times will be very variable, reasonable estimates suggest that 3m unsaturated sand & gravel *subsoil* will often be sufficient for significant microbial die-off. In general, limitations in recharge acceptance will not be significant in sand & gravel aquifers. However, opportunities for attenuation other than simple die-off also occur in unsaturated sands & gravel. As a consequence, and on the basis of results from applied field investigations, Lewis et al (1980) suggest that there will be little likelihood of bacteriological groundwater pollution .. provided there is at least 2 m of …[subsoil material].. and low hydraulic loadings can be maintained (less than 50 mm/day)”. Similarly, Metcalf

& Eddy (1991) suggest that 3 ft (~0.9m) of material is sufficient to remove most faecal coliforms and viruses.

Based on the concepts outlined in Section 4.2, the boundary between extreme and high vulnerability groundwaters in unconfined sand & gravel aquifers is therefore taken as 2m thickness of unsaturated sand & gavel subsoil material.

Subsoils act as a protecting layer over groundwater by both physical and chemical/biochemical means. Fine grained sediments such as clayey till, lacustrine clays and peats have a low permeability and consequently can act as a barrier or hindrance to the vertical movement of contaminants. Even if the permeability is sufficiently high to allow slow intergranular movement of contaminants, for instance in sandy tills or silts, the sediments can strain out and absorb bacteria and viruses. In contrast, high permeability sand & gravels can provide some attenuation and dispersion but filtration will be limited and will not, for example, provide significant attenuation of certain viruses.

In summary, the coarse, highly permeable nature of sand & gavel aquifers suggests that, in diffuse recharge conditions, groundwater will generally be more vulnerable in these materials than in other natural subsoils materials, even in unsaturated conditions. Further, velocities are such that travel times of several years or more require unsaturated thicknesses which are rarely found in Ireland. As a consequence, sand & gravel targets cannot be assigned a ‘moderate’ or ‘low’ rating unless they are overlain and confined by a sufficient thickness of moderate or low permeability subsoil.

4.6 The permeability and thickness of the subsoil materials

4.6.1 Introduction

As discussed in Sections Section 4.2 and 4.4, the permeability and thickness of the subsoils material within the pathway is the key determinant of vulnerability in areas where:

- Recharge is diffuse.
- The uppermost target is groundwater within a bedrock aquifer.
- The uppermost target is groundwater within a sand & gravel aquifer that is confined by lower permeability subsoil.

Note that the uppermost target can be groundwater within a bedrock aquifer even where the subsoil is high permeability sand & gravel, as long as the sand & gravel has a saturated thickness and an aerial extent that is insufficient to merit classification as an aquifer.

The materials under consideration can therefore have a ‘high’, ‘moderate’ or ‘low’ permeability.

The moderate to high boundary is conceptually based on sand & gravel aquifers. High permeability subsoils are those that are permeable enough to comprise an aquifer, assuming that they had a sufficient saturated thickness and areal extent. A high proportion (or even all) available recharge will infiltrate. In essence, these are sorted sand & gravel deposits, such as fluvioglacial sand & gravel, wind blown sands and beach gravel. O’Suilleabhain (2000) studied available testing data from known sand & gravel aquifers across Ireland and found that all had permeabilties generally in excess of ~10 m/day or ~10^{-4} m/s.

Moderate permeability materials are conceptually based on the properties of sandy and silty glacial tills. Low permeability materials are conceptually based on the properties of clayey glacial tills, lacustrine clays and peat. The moderate to low permeability boundary is conceptually based on recharge acceptance. Low permeability subsoils are those where, at any mappable thickness or saturation condition, only a very small proportion of potential recharge can become actual recharge. Mappable thicknesses are generally taken as those in excess of 1m to 3m (refer to Section 5). Theoretical modelling work undertaken by Fitzsimons & Misstear (*in preparation*) has provided evidence to suggest that recharge acceptance below ~0.001 m/day (~1×10^{-8} m/s) is very limited and not sensitive to thickness, hydraulic gradient, or even permeability. Fitzsimons & Misstear went on to examine estimates of recharge acceptance derived from baseflow analyses and field measurements in areas where permeability is thought to be at or below this limit. As a result of these comparisons, they suggested that recharge acceptance in low permeability materials is generally less than 30% of potential recharge on a sub-catchment scale and generally less than 15% on a field assessment scale.

This work is supported by actual field-based permeability test data from areas where there were indications that recharge acceptance was very low (Swartz et al, submitted). Laboratory values were often up to two orders of magnitude smaller than field falling head test measurements for the same material, and this was largely attributed to differences in scale and the presence of preferential pathways. The strongest link between recharge acceptance and permeability test data was identified in the field-based falling head test data. Permeabilities were all below ~2×10^{-8} m/s in the five field-based falling head tests in materials with a low recharge acceptance. Permeabilities derived from three tests undertaken in materials with a higher acceptance were all above ~1×10^{-8} m/s. Note that results from two further tests were discounted due to poor borehole construction or the presence of high permeability lenses within the test interval.

The theoretical modelling work undertaken by Fitzsimons and Misstear (in preparation) also suggested that recharge acceptance would become very sensitive to permeability and quite sensitive to thickness and saturation conditions between 0.001 m/day and 0.01 m/day (~1×10^{-7} m/s). At permeabilities above this limit, predictions have suggested that most or all potential recharge should be accepted in all but the thickest, most saturated conditions.

Taking all the data together, it is considered that the boundary between moderate and low permeability materials will theoretically be ~0.001 m/day (~1×10^{-8} m/s), when measured using field-based falling head tests. However, recharge acceptance is highly sensitive to permeabilities only slightly higher than this amount, and there are significant practical difficulties in precisely measuring field permeabilities of this magnitude. Therefore, it may be more practical to consider the boundary as comprising the range between 1×10^{-8} m/s and 1×10^{-7} m/s, if measured using field-based falling head tests.

4.6.2 Travel time in areas where the permeability and thickness of the subsoil materials is key

As described in Section 4.2, the key limits of this attribute are 100 days, several years and more than 10 years. Each of these limits will be discussed in the context of high, moderate and low permeability subsoil materials.

High permeability pathway materials:

This section considers only those high permeability sand & gravels that are either saturated for less than a few metres or that are completely unsaturated. Consequently, unsaturated zone velocities are the most critical and estimations are based on those derived in Section 4.5. Estimated thicknesses at the 100 day, 3-4 year and 10 year limits are 3m, 35m and 110m respectively.

Low permeability pathway materials:

The recharge acceptance of these materials is very low, by definition. Essentially, the materials can only transmit a fraction of the Irish potential recharge. Saturated groundwater flow is therefore expected to be dominant, and the estimations below are based on Darcy's Law (refer to Section 4.3.3).

Key parameters are recharge, permeability, hydraulic gradient and effective porosity. Permeability is assumed to be just below the moderate to low boundary; say 0.0006 m/day (~7×10^{-9} m/s). A porosity of 30% is assumed.

Hydraulic gradient is much more difficult to estimate because it will vary according to permeability and recharge. In order to fully accept a typical winter recharge rate (i.e. vertical flow) of 3 mm/day, a $1m^2$ section of subsoil with a permeability of 0.0005 m/day would require a vertical gradient of 8. In practice, vertical gradients will not generally exceed 1, explaining why the subsoil will not be able to accept all the potential recharge. A gradient of 1 is taken as a reasonable worst case value.

Assuming a gradient of 1, an effective porosity of 30% and a typical permeability of 0.006 m/day, Darcy's Law can be used to estimate a velocity in the order of 0.002 m/day.

Assuming that the estimate of 0.002 m/day is broadly representative, a travel time of 100 days would theoretically require a saturated subsoil thicknesses of less than 0.5 m. Note that mappable thicknesses are generally taken as those in excess of 1m to 3m (refer to Section 5). As a consequence, the theoretical value has been rounded-up to 1m.

Using the same velocity, a travel time of, say, 3 to 4 years would require a saturated subsoil thickness of 2 to 3 m. Similarly, a travel time of more than 10 years would require saturated subsoil thicknesses of 7 to 8 m.

Moderate permeability pathway:

The recharge acceptance of these materials is expected to be variable. Fitzsimons and Misstear (in preparation) have suggested that recharge acceptance in those materials with a permeability in excess of 0.01 m/day (~1×10^{-7} m/s) will generally be close to 100% of potential recharge. Essentially, the materials at the upper end of the moderate permeability range will be able to transmit most, if not all, of the Irish potential recharge. A mixture of saturated and unsaturated groundwater flow will therefore occur. It is assumed that travel times will generally be slower in unsaturated *subsoil* below the depth where most bypass flow mechanisms will be occurring. Saturated flow rates are therefore considered to represent a reasonable but conservative estimate of total travel time and these are the focus of the discussion that follows.

Key parameters in the saturated zone are recharge, permeability, hydraulic gradient and effective porosity. Saturated permeability is assumed to range between 1 m/day and 0.01 m/day (~1×10^{-5} to 1×10^{-6} m/s). A porosity of 30% is assumed.

Hydraulic gradient: In order to fully accept a typical winter recharge rate (i.e. vertical flow) of 3 mm/day, a $1m^2$ section of three saturated subsoils with permeabilities of 0.01 m/day, 0.1 m/day and 1 m/day would require vertical gradients of 0.3, 0.03, and 0.003, respectively. All three gradients are considered possible. In other words, and unlike the low permeability example, the hydraulic gradients are generally capable of adjusting to match the permeability and recharge. Using Darcy's Law, a porosity of 30%, and gradients that are based on a typical vertical flow rate of 3 mm/day, estimated typical vertical velocities within all three subsoils will be in the order of 0.01 m/day.

Assuming that the estimate of 0.01 m/day is broadly representative, a travel time of 100 days would require a saturated subsoil thickness of between 1m and 2m. Using the same velocity, a travel time of, say, 3 to 4 years would require a saturated subsoil thickness of 11 m. Similarly, a travel time of more than 10 years would require a saturated subsoil thickness of 30 to 40 m. Till thicknesses of this magnitude are very rare in Ireland.

4.6.3 Quantity of water and contaminants in areas where the permeability and thickness of the subsoil materials is key

As described in Section 4.2, the key limit of this attribute is 20% potential recharge acceptance.

This limit will be discussed in the context of high, moderate and low permeability subsoil materials.

High permeability pathway:

It would normally be expected that materials of this permeability would have the capacity to accept all but the most intense, short term, rainfall / recharge events and recharge acceptance will be much higher than 20%. Diamond and Shanley (1998) note that the risk of overland flow is small, even in winter months, in coarse free draining soils. Consequently, it is assumed that the entire mass of contaminants dissolved within infiltrating waters has the potential to reach groundwater in these materials.

Low permeability pathway:

As described in Section 4.6.1, Fitzsimons & Misstear (*in preparation*) have examined estimates of recharge acceptance derived from baseflow analyses and field measurements in areas of different subsoil permeability characteristics. These results are summarised in Table 4.6. As a result of these comparisons, they have suggested that recharge acceptance in low permeability materials is generally less than 30% of potential recharge on a sub-catchment scale and generally less than 15% on a field assessment scale. This latter scale is more appropriate to vulnerability assessments.

Table 4.6 Compilation of estimates of actual recharge as a proportion of potential recharge (based on Fitzsimons and Misstear, *in preparation*)

Recharge Acceptance: Actual recharge as a proportion of potential recharge		Main considerations which may help further refine the range in recharge acceptance
Thin, moderate permeability tills.	up to 90%	Aquifer properties
Moderate permeability, moderately thick (less than, say, 10m) tills.	up to 80%	Quantified estimate of till permeability, aquifer properties, confined / unconfined conditions.
Moderate permeability, thick (greater than, say, 10m) tills. Confined or semi-confined conditions.	up to 45%	
Low permeability, >5m thick sub-catchment scale	10% to 30%	Aquifer properties, confined / unconfined conditions.
Low permeability, >5m thick site scale	<5% to 15%	

Moderate permeability pathway:

Recharge acceptance in moderate permeability materials will be more variable because the range in permeability values is greater than for low permeability materials and because acceptance will also be dependent on till thickness and saturation conditions. At normal saturation conditions where there is a downward vertical hydraulic gradient, theoretical modelling undertaken by Fitzsimons and Misstear (in preparation) suggests that the values cited in Table 4.6 relate to the lower end of the moderate permeability range. At permeabilities of greater than 0.01 m/day (1×10^{-7} m/s), recharge acceptance may be even higher than 80%. Conversely, where vertical gradients are very low or are reversed (i.e *upwards*), recharge acceptance could be less than 20%. The theoretical work has also suggested that 10m saturated thickness represents a significant threshold in terms of recharge acceptance.

4.6.4 Attenuation Capacity in areas where the permeability of the subsoil materials is key

Subsoils act as a protecting layer over groundwater by both physical and chemical/biochemical means. Fine grained sediments such as clayey till, lacustrine clays and peats have a low permeability and consequently can act as a barrier or hindrance to the vertical movement of contaminants. In areas where these sediments are present, surface water is more at risk than groundwater as most if not all the contaminants cannot migrate downwards and can only move laterally. Even if the permeability is sufficiently high to allow slow intergranular movement of contaminants, for instance in sandy tills or silts, the sediments can strain out and absorb bacteria and viruses. In contrast, high permeability sand & gravels can provide some attenuation and dispersion but filtration will be limited and will not, for example, provide significant attenuation of certain viruses.

Sorption, ion-exchange and precipitation are vital chemical processes in attenuating pollutants. The cation-exchange capacity of subsoils depends on the clay and/or organic content and ranges from essentially zero for sands to about 50 meq/100g for clay soils to over 100 meq/100g for peat. Consequently, clays and peats can attenuate bacteria, viruses and chemical pollutants such as potassium and ammonium whereas clean sand and gravel has little effect. Obviously, the thicker the subsoils the greater the opportunity for cation exchange.

Similarly, longer residence times (due to slower velocities or thicker subsoils) will increase attenuation through the degradation of contaminants that are unstable in the subsurface environment. The die-off of faecal coliforms over time is a good example of this effect (refer to Section 3.2).

In general, the higher the clay content and the lower the permeability, the greater the protection of groundwater from pollution.

4.6.5 Implications for vulnerability assessments in areas where the permeability of the subsoil materials is key

The permeability and thickness of the subsoils materials will be a key factor in areas where recharge is diffuse, where the uppermost target is groundwater within a bedrock aquifer, or where the uppermost target is groundwater within a sand & gravel aquifer that is confined by lower permeability subsoil.

Extreme-high vulnerability groundwater: Though travel times will be very variable, reasonable estimates suggest that 1m to 2m moderate permeability *subsoil* (regardless of saturated thickness) or 1m low permeability *subsoil* will often be sufficient for significant microbial die-off. Based on the concepts outlined in Section 4.2, the boundary between extreme and high vulnerability groundwaters in relevant aquifers is therefore taken as 1.5m of moderate permeability subsoil or 1m of low permeability subsoils.

High-moderate vulnerability groundwater: Significant contaminant sorption, filtration, etc, is expected through moderate and low permeability materials in excess of a few metres thickness. Though moderate permeability material thicknesses of 11m are nominally required to exceed the travel time threshold between moderate and high vulnerability, it is likely in most situations that significant attenuation will occur over reduced thicknesses. For moderate vulnerability groundwater, it is assumed that a reduced thickness of 8m saturated (or unsaturated) moderate permeability material is sufficient. This figure is somewhat arbitrary and has been selected as it is equivalent to the thicknesses required for low vulnerability groundwater overlain by low permeability materials.

Though low permeability material thicknesses of 3m are nominally required to exceed the travel time threshold between moderate and high vulnerability, it is likely in most situations that significant attenuation will occur over reduced thicknesses. However, the thickness of low permeability material at the extreme to high vulnerability boundary is 1.5m. Therefore, in order to maintain a mappable difference in thickness between the two boundaries, the thickness of low permeability materials cannot be reduced significantly from 3m.

As a consequence, the boundary between high and moderate vulnerability groundwaters in relevant aquifers is taken as 3m of low permeability subsoil or 8m thickness of moderate permeability subsoil, regardless of saturation.

Moderate-low vulnerability groundwater Travel times in excess of 10 years *and* recharge acceptance of less than 20% are both key conceptual attributes of low vulnerability groundwater. Under most conditions, more than 8m of low permeability subsoil will be required to exceed the travel time threshold. In contrast, moderate permeability subsoil in excess of at least 30m are required for travel times in excess of 10 years, and recharge acceptance will not be less than 20% in moderate permeability materials unless vertical gradients are upwards rather than downwards. This combination is very rare in Ireland. Consequently, low *vulnerability* can only apply to low *permeability* materials and groundwaters are considered to have a low vulnerability where they are protected by at least 8m of low permeability subsoils.

4.7 Soil Horizons

The soil horizons can provide significant attenuation of certain contaminants, because of factors including the high organic content and the aeration provided by the flora and fauna. However, travel times through the soil horizons can be only a few hours or days. This has significant implications for the effectiveness of the soil horizons at attenuating *conservative* and *microbial* contaminants.

A substantial volume of research material, summarised by Abu-Ashour et al. (1994), Beven and Germann (1982), Thomas and Phillips (1979) and White (1985), indicates that it is an over-simplification to: (a) treat topsoils as a homogeneous medium conforming to Darcian principles of water flow, and (b) assume that the only recharge process is displacement (by piston-like flow) of all resident water and solutes by incoming water and solutes. The presence of macropores (e.g. pores formed by soil fauna (mainly earthworms), plant roots, weathering cracks and natural soil pipes) can greatly decrease the time taken for solutes and micro-organisms to migrate through the topsoil relative to predictions based on Darcian principles. As a consequence of preferential flow in macropores, gravitational flow of water can occur in soils that are well below 'field capacity' and water can move rapidly through unsaturated soil ahead of the wetting front in the soil matrix. Fleming et al. (1990) found rapid movement of faecal bacteria to tile drains and the presence of faecal bacteria at 0.5 m depth in underlying soil, following landspreading of liquid manure; they concluded that macropore flow was the most likely transport mechanism. Hallberg (1989), in a review of pesticide pollution of groundwater in the humid US, concluded that preferential flow may be making soils more susceptible to leaching of pesticides (and other land-applied compounds) to groundwater than evaluations based on traditional concepts of Darcian flux would suggest.

The role of preferential flow is likely to be less in Ireland than in some of the countries where they are shown to have a significant impact because Irish soils are relatively young (less than 16,000 years since the Ice Age ended) and climate variations (particularly temperature) are less than, for instance, the US and continental Europe. While little research has been carried out on this in Ireland, there is sufficient evidence to show that it is also an issue that is relevant to contaminant movement and groundwater protection here:

- Ryan and Noonan (1995) showed the role of macropores in soils at Johnstown Castle with a field tracing experiment where dye, applied at the surface, moved to almost 0.9 m bgl in thirteen days.

- In their review of the soil associations in Ireland, Gardiner and Radford (1980) describe the presence of roots below 0.5 m in most soils and below 1.0 m in some soils. According to Gleeson (1998), grass roots may reach depths of 2.0 m during dry summers.
- Ball (1993) has reported summer cracks in fields of pasture land down to 2.0 m. In a situation with 3-5 m soil and subsoil over bedrock, and a water table 4.0 m bgl, he found a rise in the water table of 1-3 cm and a sudden increase in faecal bacteria in the groundwater following 24 hours of intense isolated showers in June and August. He concluded that summer rainfall can bypass the soils moisture deficit and recharge the groundwater system through macropores.
- Field observations by geologists and hydrogeologists in the GSI and consulting firms report the presence of preferential flowpaths as deep as 2.0 m bgl.
- GSI automatic water level monitoring shows recharge occurring during the summer months after heavy rainfall in certain circumstances (refer to Section 4.4.2).

Preferential flowpaths are likely to exist in virtually all soils down to about 0.4-0.5 m bgl. Below this their presence will reduce with depth, depending largely on the soil and subsoil texture. In some situations, particularly where (a) the bedrock is shallow and permeable, (b) the soil and subsoil have a high clay/silt content, and (c) the underlying subsoil is sand/gravel, they may be present to depths greater than 1.0 m.

The implications are as follows:

- Bypass flows can occur at any depths but will concentrate within the soil horizons; typically to depths of up to 1m.
- Though the soil can provide excellent attenuation of certain contaminants, bypass flow mechanisms mean that conservative contaminants can penetrate the soil horizons within a few hours or days of heavy rain in many instances. This is the case even in the summer months.
- Given that the concept of vulnerability outlined in this document is independent of contaminant type, soil thickness and type cannot comprise a factor in the assessment of vulnerability. The vulnerability criteria derived in Sections 4.3 to 4.6 therefore relate to *subsoil* materials *only*.
- The nature of the soil horizons do, however, play a vital role in assessing risk and risk management measures where *degradable* contaminants are released at *surface* (e.g. landspreading of organic wastes). For this kind of activity, these considerations are accounted-for in the Irish Groundwater Protection Scheme (DELG/EPA/GSI, 1999) through the Groundwater Protection Responses.

4.8 Summary

Vulnerability represents an assessment of the ease with which water and conservative contaminants can move through the pathway to reach the groundwater within the uppermost target. This target is the groundwater within the uppermost aquifer below a site.

Vulnerability assessment criteria ***have*** been influenced by:

- Recharge type: groundwater is at its most vulnerable where rock is close to surface or below features of point recharge in karst aquifers.
- The thickness of the unsaturated zone in areas where the uppermost target is groundwater within unconfined sand & gravel aquifers.

- The permeability & thickness of the subsoil materials in areas where the uppermost target is groundwater within bedrock aquifers.

Though often key to the assessment of overall environmental risk, the development of vulnerability assessment criteria for the Republic of Ireland has *not* been influenced by:

- The bedrock aquifer category and the thickness of the unsaturated zone within a bedrock aquifer. There is thought to be minimal potential for attenuation within all bedrock aquifers. Note that the type of aquifer and assessments of flow rates will often have an influence on risk assessments of downgradient receptors.
- The thickness, permeability and attenuation potential of the soil horizons. This is due to the potential presence of bypass flow mechanisms. The soil is assessed as a separate element of risk where *degradable* contaminants are released at *surface* (e.g. landspreading of organic wastes).
- The type of contaminant. This is assessed a separate element of risk.

The vulnerability criteria have been developed on the basis of attributes relating to travel time through the pathway, the quantity of water and contaminants that can penetrate the pathway (recharge acceptance) and the attenuation capacity within the pathway.

Conceptual boundaries between the different vulnerability categories have been derived from these attributes. In concept, travel times within the pathway above highly vulnerable groundwaters should typically be in excess of approximately 100 days and the materials should be capable of capable of removing significant amounts of microbial contamination. At the other end of the spectrum, travel times within the pathway above low vulnerability groundwaters should be in excess of approximately 10 years and the materials should be capable of capable of removing significant amounts of most contaminants.

Limits of the thickness and permeability of the subsoil pathway materials have been derived from these conceptual boundaries using Darcy's Law and estimates of permeability, porosity and hydraulic gradient from what are considered to be typical values for Irish conditions:

- High permeability subsoil materials are sand & gravels that, if sufficiently saturated and aerially extensive, are capable of constituting aquifers. The lower permeability limit of these materials is ~10 m/day or ~10^{-4} m/s. Unsaturated flow is the key determinant of vulnerability. Typical vertical velocities in winter are estimated to be in the order of a 0.03 m/day.
- Moderate permeability subsoil materials are silty and sandy glacial tills that are generally quite free draining except in low lying areas and/or area of groundwater discharge. The lower permeability limit of these materials is ~0.001 m/day or ~10^{-8} m/s. Unsaturated and saturated flow will usually occur and saturated flow is the key determinant of vulnerability, assuming velocities to generally faster in the saturated zone. Typical saturated, vertical velocities in winter are estimated to be in the order of 0.01 m/day.
- Low permeability subsoil materials are clayey tills, peats and lacustrine clays that allow less than 20% recharge acceptance regardless of thickness or saturation conditions. Saturated flow will be the key determinant of vulnerability. Typical vertical velocities in winter are estimated to be in the order of 0.002 m/day.

In areas of diffuse recharge:

- 1–2 m of subsoil, and in the case of sand/gravel aquifers a 1–2 m thick unsaturated zone, below the point of release of contaminants has a sufficient protecting capacity to allow a rating of 'high'.

- High permeability sand & gravel does not have a sufficient protecting capacity, regardless of thickness, to merit a 'moderate' rating.
- A minimum of 8 m of moderate permeability sandy subsoils or 3 m of low permeability clayey subsoils, below the point of release of contaminants, enables a 'moderate' rating.
- Moderate permeability sandy subsoil does not give sufficient protection to allow a 'low' vulnerability rating, no matter how thick it is.
- At least 8m of low permeability clayey subsoil below the point of release of contaminants is needed to merit a 'low' vulnerability rating.

5 Vulnerability Assessment Issues

5.1 Introduction

The assessment of vulnerability is not straightforward because of the natural variability of the pathway materials in Ireland, and because the measurement of permeability in moderate to low permeability materials can be difficult. This Section explores some of the practical vulnerability assessment issues that may be encountered.

5.2 General Issues

5.2.1 Mapping Scale

Assessments can occur at one of two scales:

- *County/catchment scale*: Assessments are termed 'vulnerability mapping' and are undertaken by the Geological Survey of Ireland. It is assumed that the potential depth of release of contaminants lies at 1-2m below ground. This is based on the fact that point sources of pollution pose the greatest threat to groundwater in Ireland.
- *Assessments for a specific activity at a specific site*: These are termed 'site vulnerability assessments' and are usually undertaken by hydrogeological consultants. The potential depth of release of contaminants is taken from a knowledge of actual or planned site activities.

5.2.2 Depth Of Contaminant Release

The critical thickness intervals identified in Section 4 are 1m, 3m and 8m. These relate to the thickness of subsoil available to protect the target. In other words, they relate to thickness of subsoil between the point of release of contaminants and either a) the base of the subsoil (for bedrock aquifers) or b) the water table (for unconfined sand & gravel aquifers).

If vulnerability mapping is being undertaken, the point of release is assumed to be at 1-2m. Vulnerability mapping usually considers subsoil thickness in terms of depth to rock. Consequently, the critical thickness intervals of 1m, 3m and 8m are each increased by two metres to become depth to rock mapping intervals of 3m, 5m and 10m (refer to Figure 5.1).

Table 5.1 Vulnerability Mapping Criteria (adapted from DELG/EPA/GSI, 1999)

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

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

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

Table 5.1 and Table 5.2 describe how the attributes combine to produce a vulnerability assessment for mapping and site assessments, respectively.

Note that the vulnerability assessment:

- divides the study area into between one and four vulnerability categories: ‘extreme’, ‘high’, ‘moderate’ and ‘low’, based on geological and hydrogeological characteristics.
- relates to the vulnerability of groundwater in the uppermost aquifer.

Table 5.2 Geological and Hydrogeological Conditions Governing Site Vulnerability Assessment

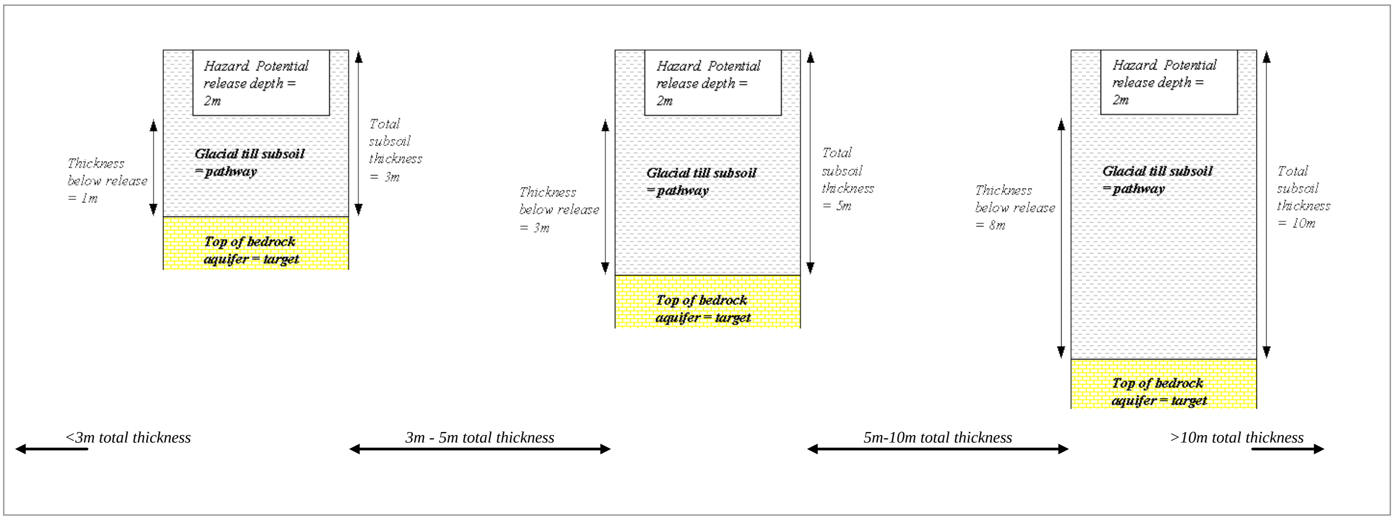
Vulnerability Rating	**Hydrogeological Requirements** ***Below the point of release of contaminants***			
	Subsoil Permeability (Type) and Thickness			**Unsaturated Zone**
	high permeability *(sand/gravel)*	moderate permeability *(sandy till)*	low permeability *(clayey till, clay, peat)*	(sand/gravel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

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

(from Daly and Warren (1998))

Note also that, in order to assist decision-makers when considering activities where the point of release is at the surface, outcrops, shallow rock and karst features are highlighted as a sub-category within the extreme vulnerability areas on vulnerability maps. Shallow rock areas are those where of rock outcrops are frequent and where topography and geomorphology suggest that the rock can be assumed to be within 1m of ground level.

Figure 5.1 Key subsoil thickness intervals expressed as total thickness and as thickness below the potential point of release of contaminants



For example, where a bedrock aquifer is overlain by a uniform subsoil of moderate permeability and total thickness of 11m, groundwater should be *mapped* as *moderate* vulnerability (refer to Table 5.1). This is because the thickness of 11m exceeds the 10m thickness interval for *mapping areas*. However, a landfill development in the same area might require a different vulnerability rating, even if subsoil thickness and permeability remained as mapped. If the landfill cells were excavated such that the maximum potential depth of release was 4m, the thickness of subsoil below this level would be 7m. This thickness lies between the 3m and 8m intervals relating to the thickness *below the point of release*. As depicted in Figure 5.1, this interval is equivalent to the 5m to 10m *mapping* interval. Consequently, a vulnerability of *high* would be assigned for the landfill site assessment.

5.2.3 Mappable Thicknesses.

Units less than 1 m in thickness are generally not considered when assessing vulnerability. Low permeability materials of only a few centimetres thickness can theoretically significantly affect groundwater vulnerability. However, materials of this thickness often 'pinch-out' over quite small distances. Contaminants would tend to reach the top of such a layer and move laterally until they reach the point where the layer disappears. At this point the barrier to vertical flow is removed and the contaminants could continue to migrate downwards towards the target. In addition, thin layers can potentially be completely penetrated by bypass flow mechanisms (e.g. tree roots). As discussed in Section 4.7, bypass flow pathways are rarely thought to exceed 1m in thickness. Consequently, layers in excess of these thicknesses are less likely to be completely penetrated and will still be able to provide some contaminant attenuation.

5.3 Vulnerability Mapping Where Point Recharge Occurs At Karst Features

Bypassing of the protecting layers of subsoil can occur where water flows rapidly underground, with minimal attenuation, at karst features such as swallow holes and dolines. Therefore, groundwater is classed as ‘extremely’ vulnerable within 30 m of karstic features, including along the area of loss of losing or sinking streams, and within 10 m on either side of losing streams upflow of the area of loss.

The distances can be varied depending on the circumstances. For instance, they can be increased where overland surface runoff is likely.

In order to assist decision-makers when considering activities where the point of release is at the surface, outcrops, shallow rock and karst features are highlighted as a sub-category within the extreme vulnerability areas on vulnerability maps. Shallow rock areas are those where of rock outcrops are frequent and where topography and geomorphology suggest that the rock can be assumed to be within 1m of ground level.

5.4 Vulnerability Mapping Where The Target Is An Unconfined Gravel Aquifer

The key factor is the depth from the point of release to the water table. In regional scale vulnerability mapping, the critical depth is 3m below ground (refer to Table 5.1). In site vulnerability assessments, the critical depth is 2m below the point of potential release of contaminants. Where values are thinner than the critical depth, vulnerability is considered to be 'extreme'. Otherwise, the vulnerability is considered to be 'high'.

The assessment of unsaturated zone thickness is usually based primarily on water level data from boreholes. However, these data are often infrequent for vulnerability *mapping* projects. In the absence of sufficient data, vulnerability mapping projects usually assume that the depth to water is in excess of 3m below ground in areas away from groundwater discharge zones such as rivers and springs.

There are situations where moderate and low permeability subsoils overlie gravel aquifers. This kind of scenario can only be assessed on a case-by-case basis. It may often be appropriate to decide if the overlying materials are of significant thickness, if the gravel aquifer is confined, and if indicators of recharge acceptance suggest that infiltration is significantly impeded across a wide area. If it appears that the subsoils overlying the aquifer are impeding drainage across a wide area, it might be argued that vulnerability is being controlled through the permeability and thickness of the overlying materials. In this scenario, vulnerability assessments would follow the principles outlined for bedrock targets.

There are several geophysical techniques which are effective in distinguishing shallow water tables in gravel aquifers; particularly where no overlying layers occur.

5.5 Vulnerability Mapping where the Target is a Bedrock Aquifer

The key factors are subsoil thickness and the permeability of the subsoil. Table 5.1 and Table 5.2 show how these factors are combined to assess vulnerability.

5.5.1 Subsoil thickness mapping

It is necessary to assess subsoil thickness across the whole area of interest. In regional-scale vulnerability mapping, total subsoil thickness is assessed using contours at 3m, 5m and 10m. For site vulnerability assessments, contour intervals will need to reflect the potential depth of release of contaminants. Optimum outputs are derived through a combination of data, knowledge and experience and subsoil thickness contours are usually inferred from a combination of:

- Outcrop and shallow rock data from the GSI and from the Teagasc Parent Material Mapping Project

- Depth to rock data from borehole databases
- Karst data from GSI databases
- Elevation and slope of ground surface
- Landscape morphology

Note that considerable variation in depth to rock is expected over a few metres of ground. Hinch (2002) examined 6 sites on limestone with detailed depth to rock data. At these sites she found that depth to rock typically varied by more than a metre across distances of as little as 3m at one site, but across distances of less than 10m across all sites. In theory, then, the contours drawn across an area could not be accurate to within a metre unless they were based on boreholes drilled on a grid spacing of only a few metres or tens of metres. Without the use of geophysics, such a spacing may not be realistic, even for site vulnerability assessments. As a consequence, contour maps of depth to rock cannot hope to be 'definitive' for vulnerability mapping projects. There is little point in adjusting contours to fit every 'anomalous' borehole data point and, in fact, such a practice would give the false impression that no anomalies occurred in areas where no borehole data existed. For vulnerability mapping, the contours should therefore be drawn so as to provide a slightly conservative, general approximation of broad trends across an area.

Additional considerations:

- Geophysics may be useful in extrapolating between points across an area. The array of commonly-used geotechnical techniques will have a role in subsoil thickness in site vulnerability assessments. The selection of appropriate geophysical techniques for larger scale vulnerability mapping projects is more problematic, given the time constraints of acquiring access to land, etc. One area of future development might be in airborne geophysics, particularly in the context of mapping areas where the rock is very close to surface.
- The need to incorporate landscape morphology and geomorphological interpretations means that simple interpolation between data points is not sufficient, when drawing contours. Consequently, computer contouring packages will not usually be suitable.
- Ice-flow directions can influence the rapidity with which depth to bedrock changes. River valleys may have the same effect.
- Outcrops may be the result of excavations (e.g. small pits or quarries, cuttings along road or railway routes, excavations for houses on the side of a slope). They may not represent rock at surface in all cases.
- Karstic areas may have anomalously deep data points within otherwise shallow rock areas, due to collapse of or infilled cavities within the rock.
- The use of cross-sections may aid in the conceptualisation of depth to bedrock in an area, especially in areas where the dip of the bedrock or topography may be a controlling factor.

In summary, borehole information are used to support, not supplant morphology and outcrop data. To this end, the contours should represent a carefully judged assessment of all the factors in any given area.

5.5.2 Permeability Assessment Methodologies

In relevant hydrogeological situations, vulnerability categorisation requires an assessment of whether the permeability of the pathway materials is either 'high', 'moderate' or 'low'. This assessment is based largely on the concept of recharge acceptance and the general question *'can water and contaminants reach groundwater easily?'*.

Permeability assessments generally comprise a three-fold process. The first involves the assessment of individual point and areal data (this Section), the second involves the consideration of vertical variations in these data (Section 5.5.4), and the third involves the consideration of spatial variations (Section 5.5.5).

The aim is to assign a permeability category of ‘high’, ‘moderate’, or ‘low’ to each data point or area under consideration. Section 4.8 provides values at the boundary between these categories.

The measurement of permeabilities at selected depths & locations will often be critical to site vulnerability assessments; particularity for major developments. Examples of tests can range from percolation tests for domestic wastewater treatment systems, to laboratory tests, to in situ falling head tests in boreholes, to full-scale pump tests. In moderate to low permeability materials, direct permeability measurements alone will rarely be sufficient:

- Different techniques often give different values (refer to Section 4.6.1), not least because they measure permeability at different scales and are influenced by preferential flow paths to differing degrees.
- The values provided in Section 4.8 relate to field-based falling head tests. However, there are significant practical difficulties in undertaking these tests in moderate to low permeability materials. It is often difficult to obtain a defensible result for moderate to low permeability materials because of the time required to await water table equilibrium prior to the test, the time required to undertake the test, and the very high standards of borehole construction required to seal off the test interval.
- The presence of thin layers of high permeability materials can significantly affect the permeability value obtained from a specific test, but may have no bearing on the recharge acceptance and the ability of water and contaminants to reach the target.

Defensible site vulnerability assessments will usually require additional considerations to both a) provide a cross-check on the permeability measurements and b) provided an overview of the overall recharge acceptance characteristics. Vulnerability mapping projects will rely almost exclusively on these additional considerations because permeability measurements will not generally be available.

The Geological Survey of Ireland and Trinity College Dublin have undertaken two specific research projects to develop proxies for assessing permeability at specific locations and to develop secondary indicators which provide an indication of recharge acceptance and vulnerability as a whole in a particular area (Lee, 1999 and Swartz, 1999).

The permeability proxies that have been developed involve particle size analysis data and the description of subsoil samples:

- *Subsoil description and classification:* The method is based on the British Standard BS5930:1999. Some additional tests have been added on the basis of descriptions of samples in known low and moderate permeability subsoils. The procedure is summarised in Appendix I and a flow chart is included. The rational behind some of the procedures is described in Appendix II.

  Using this method, subsoils described as sandy or gravelly CLAY have generally been associated with low permeability materials. Subsoils classed as silty SAND and sandy SILT, on the other hand, have generally been associated with moderate permeability materials (Swartz, 1999). In general, subsoils described as sandy GRAVELS or gravelly SANDS are associated high permeability materials. Subsoils described as SILT/CLAY are those where the field tests are not able to determine if the sample is a silt or a clay and the description can only be used to suggest that the material has *either* a moderate or low permeability. Note that, in some instances, it has been found that subsoils described as ‘clayey SAND’ have a high enough proportion of clay to behave as low permeability materials.

- *Particle size analyses.* The particle size distribution of sediments describes the relationships between the different grain sizes present. Well sorted sediments such as lacustrine clays (low permeability) will, on analysis, show a predominant grain size at just one end of the scale. Sand & gravel deposits and tills are generally more complex.

  Correlating country-wide pumping test data with particle size analyses, the boundary between moderate and high permeability sands and gravels is thought to be in the order of 7% to 8% total fines (O'Suilleabhain, 2000).

  Glacial tills are highly variable, but also conform, with exceptions, to a general pattern. On the basis of work outlined in Swartz et al. (submitted), and the analyses provided in Appendix II, tills in moderate permeability subsoils will usually have less than 35% fines (silt and clay) and less than 12% CLAY. Similarly, tills in moderate permeability subsoils will usually have more than 50% fines, and more than 13% CLAY. Note that these percentage figures represent laboratory results which have been adjusted to exclude materials larger than 20 mm.

These proxies provide supporting information for subsoil permeability but there are limitations. Exceptions particularly occur in areas where the clay mineralogy, degree of particle sorting, and density/compaction might be expected to influence permeability.

The secondary indicators of recharge acceptance that have been developed encompass drainage density, vegetation, soil type, and bedrock type:

- *Artificial Drainage Density:* Artificial drainage refers to the drainage installed by landowners to remove surplus rainwater from the land. There are two main types: shallow drainage systems and groundwater drainage systems both of which link to drains or ditches usually located around the perimeters of fields. Successful drainage depends on the spacing of the drains (Keane, 1986), which in turn has been shown to depend on soil and subsoil permeability, as well as soil and crop management and type (Schwab et al., 1993). It has been shown that in general, areas with a high density of human made drainage channels have a relatively low natural infiltration capacity and therefore lower recharge acceptance (Lee, 1999).

  The artificial drainage density is the total length of drainage ditch per unit area (m/ha). It does not relate to the density of the drainage pipes; only to the side drains (i.e. ditches) running along field boundaries. The ditches can be readily identified with field observations or with certain high resolution remote sensing techniques. Preliminary thresholds between each of the permeability categories have been identified by Lee (1999) as follows:

  - High permeability <20 m/ha artificial drains;
  - Moderate permeability 20–80 m/ha artificial drains; and
  - Low permeability >80m/ha artificial drains.

  A minimum area of investigation of at least 1 km^2 (all of similar slope and underlain by similar aquifers) is recommended by Lee (1999) to provide a representative result.

- *Natural drainage density:* The natural drainage network of an area or catchment can be characterised in a number of different ways including: drainage pattern, stream order (i.e. the larger the stream, the greater no. of tributaries and the higher the stream order), length of the tributaries, stream density (i.e. no. of streams per unit area) and drainage density (length of drainage channel per unit area). Following investigation into all these methods (Lee, 1999), drainage density was selected as the most appropriate for permeability studies. Preliminary thresholds between each of the permeability categories have been identified by Lee (1999) as follows:

  - High permeability <0.6 km/km^2 natural stream length;
  - Moderate permeability 0.6–1 km/km^2 natural stream length; and
  - Low permeability >1 km/km^2 natural stream length.

A minimum area of investigation of at least 50 km^2 (all of similar slope and underlain by similar subsoils and aquifers) is recommended to provide a representative result.

- *Vegetation.* It is well documented in the literature that certain vegetation species flourish in wet soil conditions while others prefer much drier conditions. Similarly most farmed crops require specific drainage conditions. Several studies (summarised in Lee, 1999), including some specific to Irish conditions, have identified vegetation indicator species which can be used to distinguish different drainage conditions. Many species are identified in Lee (1999), but the most common indicators of low recharge acceptance are rush, iris, alder and willow. The most common indicators of moderate or high recharge acceptance are poppies and ragwort. Note that, in heavily-managed farmland where extensive field drainage has taken place, vegetation indicators will not be a good indicator of recharge acceptance.
- *Soil type*: Poorly drained soils such as surface water gleys can often be related to underlying low permeability subsoils, while most other soil types are more typical of the sandy and silty moderate permeability subsoils. Note that soils associated with high water tables (e.g groundwater gleys) cannot be used as secondary indicators of recharge acceptance.
- *Parent material of the subsoil.* The parent material for the subsoils (usually bedrock), can be a factor. Sandstones, for example, can give rise to a high proportion of sand size grains, clean limestones can provide a relatively high proportion of silt, while shales, impure limestones and mudstones break down to the finer clay size particles. A good knowledge of the nature of the bedrock geology, the direction of movement of the glaciers, and the modes of deposition of the sediments are all therefore important. Understanding the processes at work enable predictions to be made where direct observations are lacking.

The secondary indicators can provide useful supporting information for the permeability test and permeability proxy data. In particular, they can help understand the significance of vertical changes in the subsoil and can help identify aerial subsoil permeability boundaries (refer to Sections 5.5.4 and 5.5.5). However, there are limitations that apply to most of the indicators. Clearly, certain areas will have high water tables and low recharge acceptance regardless of the subsoil permeability. These areas most commonly occur:

- At the base of slopes.
- Where iron pans occur in the soil horizons.
- In discharge zones at springs and along rivers.
- On steep slopes in areas of exceptional rainfall (e.g mountain sides).
- Where the underlying aquifer is poor.

As a consequence, the drainage density, vegetation and soil type will not be good indicators of subsoil permeability in these areas.

Note that the aggregates industry often requires sand & gravel deposits with a fines content similar to, or even lower than, the limits normally associated with high permeability materials. As a consequence, the frequency of gravel pits in a sand & gravel deposit can often provide a useful background indication of the overall permeability.

5.5.3 Assessing individual point and areal permeability data

In order to derive and assessment of the permeability category in any one location, permeably measurements are best interpreted with the support of proxy permeability tests, such as the BS5930:1999 descriptions or particle size data, and secondary indicators of recharge acceptance, where they area applicable. The data and decision-making notes are usually collated onto a single sheet for a single location. An example is presented overleaf.

For vulnerability mapping projects, it will be common for no permeability test data to be available and assessments will generally rely on the proxies and secondary indicators.

Trial Hole and Exposure Assessment Sheet

GSI — Geological Survey of Ireland / Suirbhéireacht Gheolaíochta Éireann

Site No. Sheet No. Grid Ref.: Date/time examination: Date/time excavation*: Weather:	Depth of hole or exposure ……………….. m Interval which is visible: From ……………….. m b.g.l to ………… m b.g.l Depth to bedrock ……………….. m b.g.l Depth groundwater struck* ……………….. m (seeping? flowing?) and ……………….. m (seeping? flowing?) Standing water level * ……………….. m b.g.l (during excavation) Standing water level ……………….. m b.g.l (at time of examination)	Location (e.g. townland) Topography: Vegetation, land use and drainage (e.g. rushes on slope? field drains?) Preferential pathways** (sand lenses, colour/mottling, depth top & base, width, etc)

Depth Scale	Thickness (m)	Density/ Compactness	Colour	Soil/Subsoil Type								Additional Details (e.g. interpreted origin, clast type/shape/striations, sorting, pans)	Sample No.
				Plasticity		Dilatancy		Other Factors			Name		
				Total No. Rolls	Length Ribbons	Shaking	Squeezing	Crusting?	Gritty?	Shiny?			

Info. from existing maps (if available).	Rock type
	Quaternary sediment type (i.e. soil parent material)
	Soil type.

Overall assessment / interpretation	Photo No.

*Notes: * Only relevant in trial hole and borehole excavations. ** Includes discontinuities*

Where the data are in conflict, a documented, balanced judgement will be required. This, in turn, will require an understanding of the reasons for the conflict. For example:

- If permeability test data from a borehole are suggesting moderate permeability, but data from the permeability proxies and recharge acceptance indicators in the vicinity of the borehole suggest low permeability, some consideration may be required of possible errors in the permeability test (e.g. problems with borehole construction). If errors were found, the permeability would be classed as moderate.
- Conversely, if permeability proxies suggest low permeability, but nearby recharge acceptance indicators suggest moderate permeability, it may be that the depth to rock is unexpectedly shallow or that preferential flow paths are occurring at depth. Both phenomena might allow higher recharge acceptance through lower permeability pathway materials. In this instance, the permeability would effectively be 'moderate' for the purposes of the vulnerability assessment.

However, more significant variations will occasionally occur, where the permeability category at different points in the vertical profile has been classified differently. A moderate permeability sandy SILT of 5m thickness, for example, may overly a low permeability layer of CLAY 2m thick.

In these situations, the main consideration remains: *'can water and contaminants reach groundwater easily?'*. In other words, *'do the vertical changes affect recharge acceptance through the pathway as a whole?'* If so, *'how do they affect the recharge acceptance?'*

For site assessments, the implications are best assessed with detailed BS5930:1999 descriptions in all the layers of the sequence, coupled with carefully targeted permeability tests. The descriptions would preferably be supported by particle size analyses at selected intervals, though this will depend on the nature of the hazard and the implications of changes in vulnerability on the overall risk assessment. A qualitative or quantitative analysis (as appropriate) of the flow rates through the whole sequence would then be made with a view to deriving an overall judgement on the effective permeability of the whole system. Where secondary indicators are available, this assessment would be compared with the recharge acceptance of the area as a whole.

In areas where the recharge acceptance and the assessment of flows rates are in conflict, a documented, balanced judgement will again be required. For vulnerability mapping projects, greater emphasis is usually placed on the secondary indicators of recharge acceptance when resolving apparent conflicts. When resolving apparent conflicts, it should also be noted that layers of 1m to 3m thickness will often have little effect on recharge acceptance as they can pinch-out over short lateral distances (refer to Section 5.2.1).

Clearly, these assessments require an understanding of the depth of release of contaminants. Layers impeding recharge acceptance that lie above the point of release will be irrelevant in terms of the assessment of overall permeability. An example represents the iron pans that can occur in soil horizons. These pans can extend over wide areas and can impede recharge acceptance. However, they do not require consideration for those activities potentially releasing contaminants below ground.

For both assessment scales, the aim is to derive, possibly from different permeabilities at different locations in the depth profile, a single 'effective' permeability category for the whole subsoil pathway at each location.

5.5.5 Assessing spatial variations in permeability characteristics: mapping permeability

Once the permeability categories at different depths in a subsoil profile have been assessed, and once the effective permeability of the relevant portion of the whole profile has been assessed, it will be necessary to combine all these individual assessments into a single value for an area of land. These areas could range from a few tends of square metres to many tends of square kilometres.

In other words, the whole study area requires sub-division into 'permeability units', each with a different permeability category which broadly characterises the subsoil permeability in the unit.

There will not normally be sufficient permeability data to delineate boundaries on the basis of permeability tests and permeability proxies alone. Unit boundaries are usually delineated using existing mapping (e.g. subsoils, bedrock, or soils mapping) that is thought to relate closely to differences in subsoil permeability. For example, one unit might have limestone bedrock, glacial till subsoil and brown earth soils, while its neighbour might have limestone bedrock, glacial till subsoil and surface water gley soils. If other secondary permeability indicators were not applicable in this area (perhaps due to high levels of land management), the difference in soil type might be assumed to reflect differences in subsoil permeability. If broadly supported by the point and areal data, the boundary between the two units would then be taken from the existing soils mapping. Point data and secondary indicators from each permeability unit would be amalgamated to derive a single permeability rating for each unit.

The GSI presents all the factors for a particular unit on one A4 sheet. These factors include all the BS5930:1999 descriptions and all the particle size data for the area encompassed by the unit. An element of variability is expected in most permeability units and the aim is to assign a permeability category that fits the overall balance of the data. The standard GSI assessment sheet is presented overleaf

Note that, in site assessments, geophysics could also play a part in helping to delineate permeability boundaries. Given that the permeability categories all have some conceptual link with silt and clay content, a correlation between electrical resistively and permeability category might be achievable in certain sites. Given complexities associated with degrees of saturation and clay mineralogy, such a correlation would presumably be most effective at the site-specific level and would be based on calibrations with permeability, saturation, pore water quality, and particle size data from on-site excavations.

Summary of Permeability Data and Analyses for a Permeability Unit

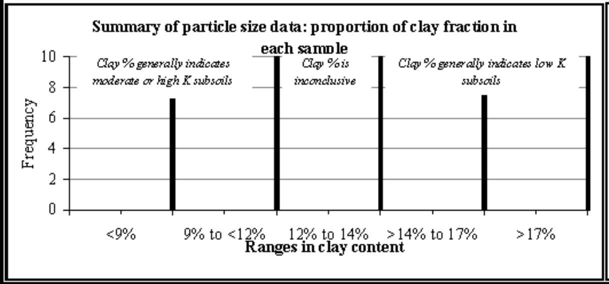
Description of unit location:	
Why is this a single K unit?	

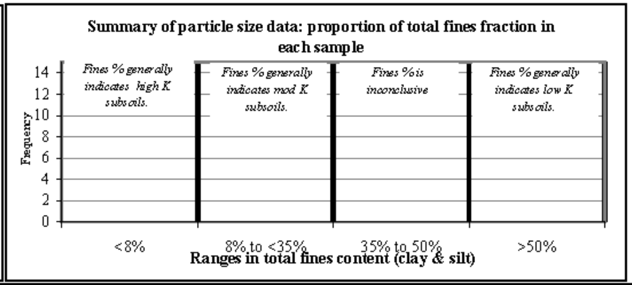
1. General Permeability Indicators and Unit Characteristics

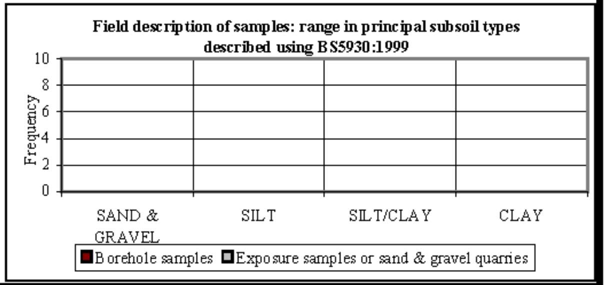
Rock type	
Depth to bedrock	
Subsoil type	
Soil type	
Vegetation and land use	
Artificial drainage density	
Natural drainage density	
Topography and altitude	
Ave. effective rainfall (mm)	

2. Summary of Particle Size Analysis and Field Descriptions of Subsoil Samples.

NB Particle distributions adjusted to discount particles greater than 20mm. Graphs only depict samples taken from 1) a known depth exceeding 1.5m in boreholes or 1m in exposures, AND 2) locations not at permeability boundaries.







3. Data from Permeability Tests.

T' tests: min/25mm	# Results	# Tests T<1	# Tests T>50	Variable head tests (m/sec):	# Results	Range Values	Typical value	Pump tests (m/sec):	# Results	Range Values	Typical value	Lab tests (m/sec):	# Results	Range Values	Typical value

4. Summary and Analysis

Criteria	Comments	Implications of each criterion for assessment of subsoil permeability
Quaternary / subsoil origin		>>>
Particle size data		>>>
Field description data		>>>
		>>>
Soil type		>>>
Artificial drainage density		>>>
Natural drainage density		>>>
Permeability test data		>>>
Rock type		>>>
Land use		>>>
	Overall conclusion	>>>

5. COMMENTS:

6 CONCLUSIONS

The basic concepts of vulnerability assessment in the Republic of Ireland are as follows:

- The target is groundwater within the uppermost aquifer below a site.
- The unsaturated zone in the bedrock has little or no capacity for contaminant attenuation.
- The *soil* horizons have little or no capacity to attenuate *conservative* contaminants released at surface.
- The pathway comprises the *subsoil* materials between the point of release and the target.
- The vulnerability of groundwater within the target relates to the travel time of conservative contaminants within the pathway, the quantity of water and contaminants that can penetrate the pathway and the attenuation potential of the pathway as a whole.
- For sand & gravel aquifers at surface, the key consideration is the thickness of the unsaturated zone between the point of release and the target. For bedrock aquifers, the key considerations are the thickness and permeability of the subsoil materials between the point of release and the target. For areas of rock at surface or point recharge in karst aquifers, the pathway is absent and vulnerability is at its maximum.

Defensible vulnerability assessments therefore require a good conceptual model of the geological framework and recharge acceptance characteristics. This understanding will assist in addressing areas where exceptions and complications arise. It will also assist in avoiding some of the common pitfalls of vulnerability assessment.

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Appendix I: Subsoil Classification and Description Based on BS5930

7.1 Principles of BS5930

Subsoil usually consists of rock particles, mineral grains and sometimes organic matter, together with variable amounts of water and air.

Engineers and hydrogeologists place a great deal of importance on the size of the rock particles and mineral grains – specifically the relative proportions of ‘coarse’ and ‘fine’ material. This is because both the permeability and the behaviour of a subsoil under loading are, in fact, closely-related concepts, which relate to the ease with which water can be ‘pushed’ out of the material. Studies at the Geological Survey and Trinity College (e.g Swartz, 1999) have linked permeability closely to the proportion of ‘fine’ material in a number of different Irish subsoil types. The purification capacity of the subsoil is also closely related to the proportion of fine material.

The terms ‘coarse’ and ‘fine’, along with their various subdivisions are associated with well-defined grain sizes.

Main Particle Size Groups

Description			**Particle Size**
Coarse Grain Sizes	Boulders		Over 200 mm
	Cobbles		60-200 mm
	Gravel	Coarse	20-60 mm
		Medium	6-20 mm
		Fine	2-6 mm
	Sand	Coarse	0.6-2 mm
		Medium	0.2-0.6 mm
		Fine	0.06-0.2mm
Fine Grain Sizes	Silt		0.002-0.06 mm
	Clay		Less than 0.002 mm

The main subsoil sediment groups in Ireland often contain mixtures of material with a variety of different particle sizes. The proportion of different particle sizes in such mixtures can be measured in a laboratory to produce a ‘particle size distribution’.

So, we know that the proportion of fines in a mixture has an influence on permeability and purification, and we have the ability to measure this proportion in the laboratory. Unfortunately, it will often not be practical to obtain particle size data, particularly if there are several layers of different subsoil materials. More significantly, the precise grain size proportion at which silt and/or clay become significant in the behaviour of a sample varies depending on a variety of other factors such as the mineralogy of the clay particles. Further, features such as cracking in the subsoil or the degree of compaction can also play important roles in percolation and purification.

In other words, we are going to have to work a little harder to assess our subsoil. The variety of different factors involved means we need to use a whole suite of descriptive procedures set within a logical decision-making framework. Further, these procedures need to be; a) based on the engineering behaviour of a sample; b) readily usable on-site; and c) able to produce descriptions with a widely-recognised meaning.

BS5930:1999 is the standard system considered by the GSI for permeability mapping. The basic principles and many of the individual field descriptive procedures outlined in BS59320:1999 have been adopted or adapted in order to achieve the following aims:

- Identify the 'principal subsoil type'. In many situations, this has been found to be the most important factor influencing the permeability of, or percolation rate through, subsoils. The principal subsoil can be one of seven types, namely; 'BOULDERS', COBBLES', 'GRAVEL', 'SAND', 'SILT', 'SILT/CLAY', or 'CLAY'.
- Identify secondary constituents and additional features which may also have some bearing on the percolation rate through, and purification capacity of, the subsoil material.

The main criteria by which the principal subsoil type is identified are as follows:

i. Is the principal subsoil type 'BOULDERS' or 'COBBLES'? Yes, if these grain sizes comprise more than half the total weight of the sample. If so, the principal subsoil type is then designated on the basis of which of the two are more common. If not…

ii. Is the subsoil 'fine' or 'coarse'? Fine subsoils stick together when wet ('cohesion') and can be rolled into a thread that supports its own weight ('plasticity').

iii. The principal subsoil type in coarse subsoils is named on the basis of their most common particle type (i.e. SAND or GRAVEL).

iv. The principal subsoil type in fine subsoils is either SILT, CLAY, or SILT/CLAY. They are distinguished mainly on the basis of their engineering properties - in particular the plasticity and dilatency - and on the basis of a variety of other properties. Silts are generally more dilatent and less plastic than clays. Plasticity and dilatency are described briefly later in this Appendix.

The individual field tests used in considering these criteria are described in more detail in the flow chart at the end of this Appendix.

The main point to remember is that, for most subsoil types, the designation of the principal subsoil type and minor constituents is based on the engineering properties of the sample. Specifically, the main properties of interest relate to the behaviour of the sample under changes in stress and water content, including:

- Cohesion
- Plasticity

BS5930:1999 uses several additional factors in describing subsoils, as follows:

texture and particle size distribution of subsoils (particularly in boulders, cobbles, gravel and sand);

- dilatency;
- bedding;
- discontinuities (particularly preferential flowpaths);
- colour;
- compactness/strength; and
- particle shape.

Cohesion and Plasticity
A sample could be thought of as exhibiting cohesion when, with a certain moisture content, its particles stick together to give a relatively firm mass. For permeability mapping, it is sufficient to think of plasticity as the ability to withstand pressure and change shape without breaking. As a rule, any subsoil considered to be 'fine' will have some plasticity. More plastic subsoils will be able to withstand pressures and change shape at lower moisture contents. In the context of field tests, this means they will be able to be rolled into a thread and re-rolled more often without breaking, because water is squeezed-out during the rolling process. In theory, more plastic materials will have a higher clay content. Clearly, both cohesive and plastic behaviour are strongly related to water content. In order to compare two samples, therefore, they should ideally both have the same water content before the tests start. This is very difficult to achieve in the field. Using the BS5930:1999 system, we recommend that samples start off the cohesion and plasticity tests with a moisture content equivalent to the consistency of putty. It is hoped that this will provide some degree of standardisation. In the laboratory, plasticity is, in fact, expressed in terms relating not to the material itself, but in terms relating to the moisture content at which its behaviour changes.

These are all considered in this document, although the descriptions are oriented towards the factors of most relevance to assessment of on-site wastewater system suitability – the identification of the principal subsoil type.

Dilatency
'Dilatency' is a geotechnical term which means 'reaction to shaking'. Suffice it to say that dilatent materials of a certain size and water content, when subjected to vibration, will 'sweat' water at the surface. They rapidly take on a 'livery' or glossy appearance, and then will lose this appearance rapidly when the sample is squeezed, or even once the vibration stops. This is due to their ability to move water through the pores spaces efficiently when those pore spaces are squeezed. Dilatency is most apparent in silts and very fine sands, where pore spaces are large enough to allow relatively rapid movement, but no so large that the sample has no cohesion. Thus, in fine materials, dilatency is useful for identifying those samples which are principally 'SILT'. Samples where the principal subsoil type is 'CLAY' should generally exhibit no plasticity. Dilatency can, in a sense, be regarded as a simple, small-scale, permeability test.

Before we move on, some important points are re-emphasised, which can easily get lost under the burden of jargon:

- The principal subsoil type can be regarded by us as the particle size group which exerts the main influence on percolation rate through the subsoil.
- The principal subsoil type uses terms which relate to particle size. However, in finer materials, the engineering properties of a sample are the main influence on the determination of the principal subsoil type.

For example, in samples where the principal subsoil type is designated as 'CLAY', the proportion of clay and silt is often at least 35% of the weight of the sample, but it may be less than 25% in some cases, depending on the behaviour of the sample. The proportion of clay itself may only make-up perhaps 15% of the total weight of the sample.

The remainder of this Appendix describes the various field tests involved in identifying the principal subsoil type and secondary constituents, along with presenting standards for describing useful additional features such as bedding and particle shape.

As mentioned above, these tests are based on the principals and procedures outlined in BS5930:1999. It is quite easy to become bogged-down in these procedures. However, additional tests and some more specific criteria have been added. These have been developed by examining samples which are from areas where the subsoil permeability is of little doubt. The derivation of these additional criteria is provided in Appendix II. A summary flow chart is presented in at the end of this Appendix which is an adaptation of BS59030:1999 and will hopefully provide some clarity. It is advised that this chart becomes the focus, referring back to the main text only if additional detail is required.

7.2 STEP 1: GENERAL OBSERVATIONS

Examine the exposure before examining any samples. Observe slope of sidewalls:

- Are they smeared?
  - If **yes**, the subsoil is probably dominated by SILT or CLAY or CLAY/SILT
  - If **no**, probably a SAND and/or GRAVEL, especially if the sides of the pit are also unstable.
- Is there water seeping in?
  - If **yes**, the water table is high or there is a perched water table in a coarse pocket within an otherwise fine grained deposit.
  - If **no**, water table is below the bottom of the trial pit.

7.3 STEP 2: BEDDING

In exposed cuttings, it is important to look for the presence of beds (layers), laminations (thin layers of fine grained sediments) or lenses of different sediments. The beds are usually layered horizontally or at a slope, forming distinct units of sediment of different grain size. In some exposures inter-bedding of silt and sand may be found. In others, there may be sand or gravel lenses in a dominantly clayey deposit. These may be important in explaining results from percolation tests. For instance, a bed of clayey sediments in an otherwise coarse grained sediment could hinder the vertical movement of effluent and cause the system to fail. Also, a thin sand or gravel bed or lens could give an apparently adequate permeability during a field test, which might not reflect the recharge acceptance characteristics of the whole subsoil profile.

Scale of Bedding Thickness and Terms to Use

Term	Mean Thickness (mm)
Very thickly bedded	over 2000
Thickly bedded	600 to 2000
Medium bedded	200 to 600
Thinly bedded	60 to 200
Very thinly bedded	20 to 60
Thickly laminated	6 to 20
Thinly laminated	under 6
Interbedded	Alternating layers of different types pre-qualified by thickness term if in equal proportions. Otherwise, thickness of spacing between subordinate layers defined.

Note the depth to the top and to the base of each bed. In laminated materials, it may be helpful to group sequences of beds together for this purpose.

A subsoil description (STEPS 4 to 13) will be required for each individual bed encountered. Note that the same material type is sometimes repeated in two or more beds, particularly where the bedding is laminated or interbedded. In cases such as these, only one subsoil description is required for each type of material.

7.4 STEP 4: DECIDE ON PRINCIPAL SUBSOIL TYPE

The identification of the principal subsoil type is the most important part of the subsoil description procedure. It will have a strong bearing on the assessment of overall subsoil permeability.

The identification process outlined below might appear complicated (perhaps unnecessarily so), but it should become clearer and easier with practice! The flow chart at the end of this Appendix has been drawn-up to provide an all-in-one overview of STEP 4. People have found that this diagram makes things easier and it is recommended that it becomes the focus of your attention while learning the procedures. The following notes provide some back-up information and should be read in conjunction with the flow chart.

Remember to note the results of all tests. This will be particularly important where the results of each individual test are conflicting. This is an unfortunately common occurrence.

STEP 4A: Evaluate Proportion of Cobbles and Boulders

- If more than 50% of sample is larger than 60 mm, then the principal subsoil type subsoil type is either ‘COBBLES’ or ‘BOULDERS’.
  - If most particles are >200 mm, the principal subsoil type is ‘BOULDERS’.
  - If most particles are <200 mm, the principal subsoil type is ‘COBBLES’ (see Table 3.7 for more details).
  - Either way, the next step is to determine composition of finer secondary constituents (proceed to **STEP 5**)
  - If less than 50% of sample is larger than 60 mm, proceed to **STEP 4B**.

It may, in practice, prove quite difficult to evaluate the proportion of these large particles if they are quite common in the face of the pit (i.e. in borderline situations). In some circumstances, it may help to excavate a quite large sample and divide it into two buckets: one for cobbles and boulders and one for the finer material. The relative weight of each may help to determine which is more abundant.

STEP 4B: Prepare and Examine the Hand Sample

Use the following procedure for describing each bed within the trial pit, starting at the top:

- Using a hammer, trowel, or pick, clean off a portion of the trial pit wall.
- Collect a hand-sized representative sample.
- Remove particles larger than 2 mm, as far as possible. It may be faster, particularly if several parties are looking at the material simultaneously, to use one of the particle size sieves used in soils laboratories, if available.
- Crush clumps of subsoil.
- Slowly add water (preferably as a fine spray), mixing and moulding the sample until it is the consistency of putty.

STEP 4C: Decide on Cohesion

Cohesion has already been described. Once the sample is at the appropriate moisture content (i.e. at the consistency of putty, with no cracking, stickiness or water films visible at the surface), squeeze it in your fist - does it stick together?

- If **no**, sample is probably 'coarse', i.e. SAND and/or GRAVEL, and the principal subsoil type is then designated on the basis of which of the two is more common. Proceed to **STEP 4G**
- If **yes**, sample is probably 'fine', i.e. SILT or CLAY or SILT/CLAY. Proceed to **STEP 4D** .

STEP 4D: Decide on Plasticity

Plasticity has already been described. There are a number of different field tests of plasticity in the literature. They are all quite tricky in that they require a certain amount of patience and 'lightness of touch'. Neither of these are usually forthcoming in the rain in December, but, unfortunately, establishing the degree of plasticity in a sample is very important in fine soils and every effort should be made to approach the test as rigorously as possible. The test version found by the GSI to be the easiest to be the most straightforward is described in the text accompanying the flow chart.

Please note the following important points while undertaking the test:

- Make sure the sample is the consistency of putty.
  - If too dry (e.g. surface cracking on sample), add extra water.
  - If too wet (sample sticky or a water sheen visible at surface), add extra dry subsoil to soak up excess water.
- This is a very important first step. Samples that are too wet will produce erroneously high plasticity evaluations, and visa versa.
- Check that no particles greater than 1 or 2 mm occur in the prepared sample.
- Be GENTLE and patient when rolling the sample into a thread – excess force may beak the thread regardless of the plasticity of the sample.
- When rolling the thread for the first time, it should end-up as a 3 mm thick thread and about the length of your palm. Remove excess sample before continuing, or the thread will become unwieldy.

- Once rolled, crush the thread and try again. DO NOT add water once the test has begun (i.e. whilst rolling or re-rolling the thread). This will prolong the test and give wrong results.
- The number of times you are able to roll the thread will dictate your plasticity rating. (refer to the flow chart)
- It is recommended that the test be repeated at least twice, and perhaps more if results vary. Obviously, water can be added before the test is repeated, to return the sample to the consistency to that of putty. If possible, use different pieces of the original sample for each test.

STEP 4E: Using the Ribbon Test to Augment Plasticity Evaluation

The ribbon test is not a standard test used in BS5930:1999. However, it is used by subsoil and soil scientists across the world, and is included here to help in the evaluation of plasticity. It is regarded by some as an easier test than that outlined in STEP 4D, but the temptation to use it instead of STEP 4D should be resisted.

The test procedure and decision making criteria are described in the flow chart and accompanying text, but please note the following important points:

- This test will require more sample than the plasticity test.
- It is again important to review STEP 4B, making sure the sample is the consistency of putty.
  - If too dry (e.g. surface cracking on sample), add extra water.
  - If too wet (sample sticky or a water sheen visible at surface), add extra dry subsoil to soak up excess water.
- Check that no particles greater than 1 or 2 mm occur in the prepared sample.
- Squeeze-out a ribbon and measure the length as described in the flow chart and accompanying text. The length of the ribbon is the basis used in assessing plasticity. DO NOT add water whilst squeezing-out the ribbon.
- The ribbon test can produce variable results and it is recommended that you use the average length of at least 3 repetitions. Water can be added between each test repetition, to return the sample to the consistency of putty.
- Compare with results of thread plasticity test (STEP 4D), using the flow chart and accompanying text. Ideally, the length of the ribbon should correspond with your plasticity rating. For example, a sample which ‘produced’ more than five rolls in the thread test (i.e. ‘high’ plasticity) should, hopefully, produce average ribbon lengths of, say, 10 cm. Often they wont, however. In this instance, redo both tests. If there are still discrepancies, you may have to rely on the results of other tests to help you in your final decision. Remember to pay particular attention to contradictions such as these in your notes.

STEP 4F: Using Dilatency to Assess Fines

Dilatency has already been described. Tests are fairly straightforward to carry-out, but can be very difficult to interpret, until ‘you get your eye-in’ - you will often find yourself squinting at a small sample in your hand, probably in the rain, trying to see if you can see a thin sheen of water. There is no easy way out of this, but it may help to try and see unquestionably ‘rapid’ dilatency before you do a test in anger. Any fine builder’s sand should be adequate for this purpose.

The test procedure and decision making criteria are described in flow chart and accompanying text, but please note the following important points:

- The sample should be slightly more wet (and softer) than for a plasticity test, but not so wet that free water is visible at the surface.

- The basis of the test is that the sample is vibrated and squeezed. The speed with which water appears at the surface and then disappears will fall into one of three dilatency categories – 'dilatant', 'dilates with difficulty or results are unclear', and 'not dilatant' (refer to the flow chart).
- SILT and SAND should have clear dilatancy. CLAYS should have no clear dilatency.

STEP 4G: Complete Principal Subsoil Name

Compile the above information to derive the principal subsoil name for the hand sample. This name is assigned capital letters. The assessment may often have to be a balanced compromise, in instances where one or more of the above tests give contradictory results.

Most problems occur in distinguishing between 'SILT' and 'CLAY' when the proportions of each are similar. It may help in these deliberations to note that, compared to SILTS, samples where the principal subsoil type is CLAY usually:

- have a shiny appearance when the sample (as prepared in STEP 4B) is 'smeared' by a finger or cut with knife.
- form harder lumps after the thread has broken-up in the plasticity thread test.
- disintegrate in water more slowly.
- produce a 'crust' of material around the palm on the hand. After tests 4B to 4F have been completed, allow the hand (on which the tests were performed) to dry naturally. Slap both hands together a few times to brush-off excess material. The crust should then be visible in small patches around the rim of your palm.

Where the deliberations between SILT and CLAY are genuinely inconclusive, BS5930:1999 recommends that the hybrid term 'SILT/CLAY' may be used.

7.5 STEP 5: DECIDE ON THE NAME OF THE SECONDARY CONSTITUENT.

Secondary constituents provide an additional level of information to augment the description provided by the primary constituent.

For example, a GRAVEL might be 100% composed of gravel (i.e. a 'pure' gravel), or might be a 'sandy GRAVEL' (perhaps 20% of the weight of the sample consists of sand), or even a 'clayey GRAVEL' (perhaps 10% of the weight of the sample consists of clay). Clearly, the distinction provided by the secondary constituent would be very important in this instance for a quarry owner. It is also useful for permeability mapping.

A summary of BS5930:1999 procedures with regard to secondary constituents is as follows:

- One or more secondary constituents can be selected. The dominant secondary constituent comes, in lower case letters, immediately before the principal subsoil term. For example, a 'silty, sandy GRAVEL' would contain more sand than silt.
- Identification and description of the secondary constituent(s) is based on well-defined boundaries, relating to the proportion of the total weight of a sample. For example, a 'slightly clayey, very sandy GRAVEL', will apply to a gravel subsoil with >20% sand, and <5% clay by weight. Note that this emphasis on precise particle size proportions is different to the system used to derive the principal subsoil type, which is based mainly on the engineering properties of the sample.
- 'Silt' and 'clay' are mutually exclusive. Thus, 'silty CLAY', 'clayey SILT' or 'silty, clayey GRAVEL' are combinations which cannot be used. Where the hand tests are genuinely inconclusive, the hybrid term 'SILT/CLAY' may be used.

More details on the precise boundary limits on terms such as ‘slightly’ and ‘very’ can be found in the BS5930:1999 document. For permeability mapping, however, we will not worry too much about precise proportions when undertaking field descriptions. This is because identifying the principal subsoil type is hard enough in many Irish materials, and because precise particle size data will not always be available. Our identification of the secondary constituent the depends on whether the sample is generally ‘coarse’ or ‘fine’, as follows:

- Fine materials. Generally speaking, if a CLAY, SILT, or SILT/CLAY feels gritty, we can assign it a ‘sandy’ secondary constituent (e.g. ‘sandy CLAY’). If, however, the gravel-sized grains appear more common than sand, we can use the term ‘gravelly’, perhaps elaborating, in the additional comments on whether we think the gravel is fine or coarse. If no discernible gravel or sand grains occur, there is probably no need to identify a secondary constituent.
- Coarse materials (BOULDERS, COBBLES, GRAVELS, or SAND). Try to isolate the finer ‘matrix’ lying in-between the grains of the principal subsoil type. Use the cohesion, plasticity, and dilatency tests outlined in the flow chart (and STEPS 4B to 4G above) to identify the material which dominates the behaviour of this matrix. This material can then be used as the secondary constituent term. Again, if there is no discernible gravel, sand, silt, or clay matrix, there is probably no need to identify a secondary constituent.

7.6 STEP 6: DENSITY/COMPACTNESS

The density or compactness of the subsoil may have some bearing on the percolation rate through the material. Using BS5930:1999, it can be approximately assessed on the basis of simple field tests. Terms vary depending on whether the principal subsoil type is ‘coarse’ or ‘fine’.

- Remember to examine the density/compactness of each bed where a subsoil description is required (refer to STEP 2).
- Use fresh exposures and the criteria supplied in the tables below.

Terms for Coarse Grained Subsoils (BOULDERS, COBBLES, GRAVELS, SANDS)

Term	Field Test
Very loose	Can be excavated by hand.
Loose	Can be excavated with a spade.
Dense	Requires a pick for excavation.
Slightly cemented	Visual examination, pick removes soil in lumps which can be abraded.

Terms for Fine Grained Subsoils (CLAYS, SILTS, SILT/CLAY)

Term	Field Test
Uncompact[1]	Easily moulded or crushed by fingers.
Compact[1]	Can be moulded or crushed by strong finger pressure.
Very soft	Finger easily pushed in up to 25mm.
Soft	Finger easily pushed in up to 10mm.
Firm	Thumb makes impression easily.
Stiff	Can be indented slightly by thumb.
Very stiff	Can be indented by thumbnail.
Hard	Can be scratched by thumbnail

[1]*These terms are generally reserved for silts and silt/clays.*

7.7 STEP 7: DISCONTINUITIES (PREFERENTIAL FLOW PATHS)

Discontinuities (also called preferential flow paths) can be thought of as breaks in the overall mass of a particular subsoil bed. They can be horizontal, vertical or somewhere in-between. In theory, they could be any one of a large number of features from rabbit burrows to drying cracks. Generally, though, in Ireland they will come in the form of deep plant roots and/or small lenses of sand. They can play a role in easing the passage of contaminants through the subsoil because the allow percolating water to 'by-pass' the slower flow mechanisms which operate in pore spaces. They therefore generally increase the likelihood of contamination occurring. This is particularly the case where subsoils are thin.

- Remember to examine the discontinuities in each bed where a subsoil description is required (refer to STEP 2).
- Within each *subsoil* bed, look at the exposure face for discontinuities including roots, burrows, fractures, joints, etc.
- BS5930:1999 gives a set of simple field tests, but the key element to examine is the width of the deeper discontinuities and whether they penetrate moderate or low permeability layers (i.e. whether they can influence the drainage of water and contaminants).

7.8 STEP 8: COLOUR

This is the most obvious and easily determined of subsoil characteristics. It can often help in assessing organic content, and can give an indirect indication of areas where drainage is impeded (i.e. where the percolation rate is slow):

When subsoils are well aerated (when air moves freely through the void spaces), iron can be oxidised to its highest state (Fe^{+3}) and this gives a reddish/brownish (rusty) colour.

Subsoils that are saturated have a different colour; water replaces the air in the void spaces, oxygen cannot move through the subsoil and the subsoil becomes anaerobic, or without oxygen. Subsoil that always remains saturated usually has a grey colour since the iron is reduced by bacteria to Fe^{+2}, a non-colour state.

Subsoils that have fluctuating wetness conditions, where it is saturated in winter and spring and well aerated in the summer and autumn, develop a distinctive blotchy colour pattern of mixed rust colours and grey colour that is called **mottling**.

Subsoils containing peat or organic matter usually has a dark or blackish colour.

However, there are limitations; for instance, mottling along root zones in a clayey subsoil can indicate bypass or preferential flow. Limestone has a grey colour; therefore fine grained subsoils composed mainly of limestone will tend to have a grey colour. Aerated conditions in limestone will be indicated by a brownish tinge to the grey rather than a brown colour, although at depth there may be little indication of the brown colour. In fine grained subsoils composed mainly of red sandstone, the reddish colour will still be dominant even where the subsoil is saturated.

The field procedure:

- Observe and note the colour of each bed, including mottling.
- Always try to describe the colour of beds at the same sample moisture state; either dry, moist or wet.

7.9 STEP 9: PARTICLE SHAPE FOR DESCRIBING CLASTS

Particle shape is not a critical factor in describing subsoil permeability. However, it can help in distinguishing between sediments that are water-lain, such as fluvioglacial gravels, and those deposited by ice, such as till. In the former, clasts are usually rounded or subrounded, whereas in the latter, clasts are angular or subangular.

If the bed contains gravels, cobbles or boulders, the shape of these can be described using the table below.

Criteria for Describing Particle Shapes

Criteria	**Description**
Particles have sharp edges and relatively plane sides with unpolished surfaces.	Angular
Particles are similar to angular description but having rounded edges.	Subangular
Particles have nearly plane sides but have well-rounded corners and edges.	Subrounded
Particles have smoothly curved sides and no edges.	Rounded

7.10 STEP 10: MINOR CONSTITUENTS

These can include constituents such as boulders, pockets of peat, and bricks They may be significant in terms of identifying the origin of the material, but may only make up a perhaps 1% of the total weight of the subsoil. In other words, this step can be used to note any other distinguishing characteristics of a subsoil.

Describe the frequency of each minor constituent using the terms:

- Rare
- Continuous
- Abundant/frequent

Examples: ‘rare shelly fragments’. ‘abundant gravel and cobbles’.

The latter example highlights a question which arises from time to time: ‘when does a secondary constituent become a minor constituent?’ In practice, it might be difficult to decide whether, for example, the gravel content in a sandy CLAY is such that it should be termed a ‘gravelly sandy CLAY’ or a ‘sandy CLAY with abundant gravel’

The BS5930:1999 indicates that a minor constituent is present in a material at quantities ‘which are more likely to be relevant to the geology … than to the engineering behaviour of the soil (for example less than about 10% in a fine subsoil or 1% in a coarse soil)’. The first part of this statement is more important to us than the second (not least because we’re unlikely to have a particle size distribution). Thus, in our example, we would use ‘gravelly sandy CLAY’ if we believed that the gravel content was sufficient to influence the percolation or purification efficiency of the material. Conversely, we would use ‘sandy CLAY with abundant gravel’ if we believed that the gravel content was sufficiently small as to only influence the geological interpretation of the material.

Even without engineering, hydrogeological, or geological considerations, the minor constituent can play a very useful role in helping to develop a ‘mental picture’ in the mind of someone who didn’t have the opportunity to actually see it.

7.11 STEP 11: STRATUM NAME/INTERPRETATION

This step involves attempting to identify the origin (or 'mode of deposition') of the material in question. This interpretation may help in addressing questions such as 'how far is the material likely to extend beyond the walls of the pit?' For example, 'esker gravels' may only extend a few tens of metres across, while 'lodgement till' might extend many kilometres.

The interpretation is usually made on the basis of principal subsoil type, secondary constituents, minor constituents, landform shapes, etc. It need only be undertaken by those with some form of training in Quaternary Geology.

- Compare your assessment with any names which have already been mapped.
- If you don't feel confident, add a question mark.
- Write all interpretations in brackets and in capital letters at the end of the description.

Examples: (BURREN LIMESTONE), (FLUVIOGLACIAL DEPOSITS), (ESKER GRAVELS), (LODGEMENT TILL), (TILL).

7.12 STEP 12: ADDITIONAL COMMENTS

If you see something relevant which has not already been described, add it in at the end in brackets. For example, it is useful to describe the most common lithology of the boulders, cobbles and gravel particles. For example '(gravels are of grey limestone)'. It may help to distinguish these comments from the main description if they are placed in brackets at the end.

Other examples: (poorly sorted), (clasts are striated).

7.13 STEP 13: NOMENCLATURE

Steps 1 to 12 describe the process by which material from each significant bed in the trial pit is described. The resulting terms are normally described in the following order:

- Density/Compactness - STEP 6.
- Discontinuities (if present) – STEP 7
- Colour - STEP 8.
- Secondary constituent(s) (if significant) - STEP 5
- Principal constituent - STEP 4. Write in capitals.
- Minor constituents (if significant) – STEP 10
- Particle shape (if relevant) – STEP 9.
- Stratum name (if possible) – STEP 11. Place terms in capitals and in brackets.
- Additional comments – STEP 12.

Some examples are as follows:

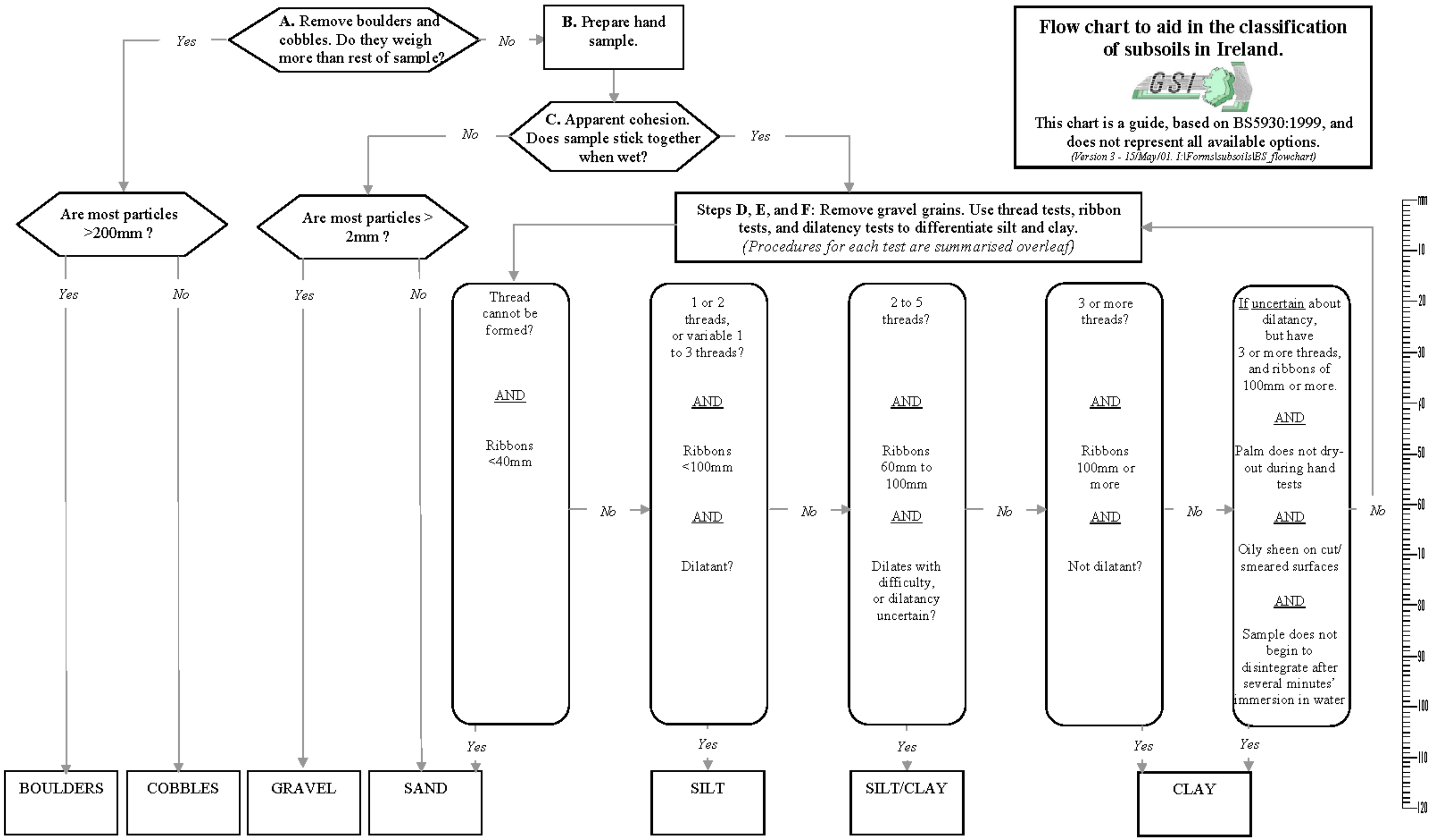
Loose, sandy, rounded and subrounded, fine to coarse, limestone GRAVEL, with occasional sand beds. (ESKER) (Poorly sorted)

Firm, thinly laminated, grey CLAY, with closely spaced thick laminae of silt and fine sand. (ALLUVIUM)

Dense, very thickly bedded, brownish-grey, clayey, SAND (LODGEMENT TILL) with rare thin sand lenses. (Consolidated, sandy, free draining.)

Very stiff, grey, sandy, gravelly CLAY. Clasts are limestone and are subangular. (LIMESTONE TILL) (Clasts are striated; there is a high silt content although clay is the dominant grain size; percolation appears impeded.)

Field equipment checklist for describing subsoils
Pick
Pronged (forked) hammer or pick
Pen knife
Notebook/trial pit description sheet
Tape measure and/or ruler
Water bottle, preferably with a spray nozzle
Camera



Secondary Constituents
NB under BS5930, determinations of secondary constituents are made using grain size data. The following guides are intended only for initial field studies.

<u>BOULDERS, COBBLES and GRAVEL</u>:
Remove particles belonging to the principal subsoil type and examine remainder of sample according to steps C to F above.

NB: More than 1 constituent can be named, if appropriate, but the terms "clayey" and "silty" are mutually exclusive under BS5930:1999.

<u>SAND</u>:
Cohesive samples / readily dilatant → "silty"
Cohesive samples / dilates with difficulty → "clayey"
Gravels common → "gravelly"

NB: The terms "clayey" and "silty" are mutually exclusive under BS5930:1999. "Gravelly" can be used with either term.

<u>SILT, CLAY and SILT/CLAY</u>:
Gritty feel and raspy sound → "sandy"
Gravels more than approximately 1/3 of total weight → "gravelly".

NB: Both 'sandy' and 'gravelly' can be used, if appropriate. However, the terms "clayey" and "silty" are mutually exclusive under BS5930:1999.

Text to accompany flow chart:

Particle Sizes as defined in BS5930:1999

Boulder	>200 mm	Larger than a soccer ball
Cobble	60-200 mm	Smaller than a soccer ball, but larger than a tennis ball
Gravel	2-60 mm	Smaller than a tennis ball, but larger than match heads
Sand	0.06-2 mm	Smaller than a match head, but larger than flour
Silt	0.002-0.06 mm	Smaller than flour (*not visible to the naked eye)*
Clay	<0.002 mm	Not visible to the naked eye.

A: Examine Boulders & Cobbles
Test adapted from the *British Standards Institution BS 5930:1999 Code of Practice for Site Investigations* (1999).

- Using a hammer, trowel, or pick, clean off a portion of the trial pit wall.
- Examine whether the quantity of boulders/cobbles is dominant over finer material. This will usually be easily done by eye. If unsure, separate boulders/cobbles from finer material in two sample bags and compare weights by hand.

B & C: Preparation of Sample and Apparent Cohesion Test
Test taken from the *British Standards Institution BS 5930:1999 Code of Practice for Site Investigations* (1999).

- Collect a hand-sized representative sample from the cleaned-off portion of the trial pit wall.
- Remove particles larger than 2 mm, as far as possible.
- Crush clumps of subsoil and break down the structure of the sample.
- Slowly add water (preferably as a fine spray), mixing and moulding the sample until it is the consistency of putty; it should be pliable but not sticky and shouldn't leave a film of material on your hands. Can the sample be made pliable at the appropriate moisture content?
- If it can, squeeze the sample in your fist - does it stick together?

D: Thread Test
Test adapted from a combination of the *American Society of Testing and Materials Designation Standard practice for description and identification of soils (visual-manual procedure) (1984),* and the *British Standards Institution BS 5930:1999 Code of Practice for Site Investigations* (1999).

- Ensure the sample is of the consistency of putty. This is very important! Add extra water or sample to moisten or dry the sample.
- Check that no particles greater than 1 or 2 mm occur in the prepared sample.
- Gently roll a thread 3mm in diameter across the width of the palm of your hand. Remove excess material.
- If a thread can be rolled, break it and try to re-roll without adding additional water.
- Repeat until the thread can no longer be rolled without breaking.
- Record the total number of threads that were rolled and re-rolled.
- Repeat the test at least twice per sample. Water can be added between each test repetition, to return the sample to the consistency of putty.

E: Ribbon Test
Test adapted from the *United States Department of Agriculture Soil Conservation Service Soil Survey Agricultural Handbook 18.* (1993).

- Ensure the sample is of the consistency of putty. This is very important! Add extra water or sample to moisten or dry the sample.
- Check that no particles greater than 1 or 2 mm occur.
- Form your moist sample into a large roll in your hand, approximately the width of your thumb.
- Hold your hand and arm parallel with the ground. Using your thumb, press the sample over your index finger to form a uniform ribbon about thumb-width and 0.5cm thick. Let this ribbon hang over your index finger and continue to extrude the ribbon between thumb and index finger until it breaks. Be careful not to press your thumb through the ribbon.
- Measure the total length of the formed ribbon when it breaks (i.e. from tip of thumb to end of ribbon).
- Repeat this test at least 3 times per sample to obtain an average ribbon value. Water can be added between each repetition, to return the sample to the consistency of putty.

F: Dilatancy Test
Test taken from *British Standards Institution BS 5930:1999 Code of Practice for Site Investigations* (1999).

- Wet the sample such that it is slightly more wet (and softer) than for a thread test, but not so wet that free water is visible at the surface.
- Spread the sample in the palm of one hand, such that no free water is visible at the surface.
- Using the other hand, jar the sample 5 times by slapping the heel of your hand or the ball of your thumb. Take note of whether water rises to the surface or not, and how quickly it does so.
- Squeeze the sample, again noting if the water disappears or not, and how quickly.
- Dilatant samples will show clear and rapid emergence of a sheen of water at the surface during shaking, and clear and rapid disappearance from the surface during squeezing. Non dilatant samples will show no discernible sheen.
- Decide whether your sample has dilatancy. Beginners often find it quite difficult to determine the presence of a sheen, unless it is very obvious. It will become easier once samples with clear dilatancy are observed.

BS5930:1999 Criteria for describing density/compactness (fine subsoils)

Term	*Field Test*
Uncompact	Easily moulded or crushed in fingers
Compact	Can be moulded or crushed by strong finger pressure
Very soft	Finger easily pushed up to 25mm
Soft	Finger pushed up to 10mm
Firm	Thumb makes impression easily
Stiff	Can be indented slightly by thumb
Very stiff	Can be indented by thumb nail
Hard	Can be scratched by thumb nail

BS5930:1999 Criteria for describing discontinuities

Term	*Mean spacing (mm)*
Very widely	>2000
Widely	2000-600
Medium	600-200
Closely	200-60
Very closely	60-20
Extremely closely	<20
Fissured	Breaks into blocks along unpolished discontinuities
sheared	Breaks into blocks along polished discontinuities

Appendix II: A Review of the use of BS5930:1999 Descriptions and Particle Size Analyses for Helping to Assess Subsoil Permeability

7.14 BS5930 Review

Purpose of review

To examine the link between results from BS5930:1999 descriptions and ‘known’ subsoil permeability on the basis of a combination of new GSI data from field vulnerability mapping from the Monaghan, Roscommon and Kilkenny Groundwater Protection Schemes, along with the data from Swartz (1999) and Lee (1999).

Method

- Take samples where surface indicators provide strong basis to pigeonhole the sample into ‘low’ or ‘mod’ K.
- Group thread, ribbon and dilatency results and qualitatively examine any differences between ‘mod’ K and ‘low’ K samples.

NB: Many more ‘unambiguous’ samples are available for ‘low K’ than for ‘mod K’, due to uncertainties about the influence of land management in apparently well-drained areas. For mod K analyses, it may also useful, therefore, to identify thread, ribbon, and dilatency groups into which low K samples do NOT fall, rather than concentrating on groups into which mod K samples DO fall.

Results

Thread tests: overlap between mod K and low K at 3 threads.

Ribbon tests: overlap between mod K and low K at 80 to 100mm ribbons.

Dilatency tests: overlap between mod K and low K at ‘slight’ (i.e. ‘slow’) dilatency.

Thus, the overlaps are quite constrained and appear to be well-defined.

However, theses overlaps can be reduced further, when combinations of the results of thread, ribbon and dilatency tests are used.

Thread and ribbon combined: No apparent overlap with available data. 3 threads and 80-100mm ribbons appear to be mod K, while 3 threads and >100-120mm appear to be low K. However, given the problems with water content and the ribbon test, definitive pigeonholing of samples into either 80 to 100mm or >100 to 120mm will probably be unrealistic in the field.

Thread, ribbon and dilatency combined: Samples close to the borderline (i.e. 3 threads and 80-100mm or >100-120mm) can be pigeonholed more definitively if the dilatency is either clear or absent. There is still some uncertainty around samples close to the borderline where the dilatency is indistinct. The use of ‘SILT/CLAY’ is probably the best solution here.

Conclusions

- There is a quantifiable basis to link thread, ribbon and dilatency tests to CLAY and SILT.
- The use of combinations of thread, ribbon and dilatency results should help improve confidence in the descriptions.

7.15 Particle size analysis review

Purpose of review

To examine the link between results from particle size analysis of clay and silt content with 'known' subsoil permeability using a combination of new GSI data from field vulnerability mapping from the Monaghan, Roscommon and Kilkenny Groundwater Protection Schemes, along with the data from Swartz (1999) and Lee (1999).

Note that these percentage figures represent laboratory results which have been adjusted to exclude materials larger than 20 mm.

Method

Use data from Monaghan, Roscommon and Kilkenny PLUS data from Swartz (1999).

- Examine influence of fines by updating Melissa's gravel-sand-fines ternary diagram.
- Examine influence of sand by revising Melissa's ternary diagram to include only sand-silt-clay.
- Examine influence of clay and clay ratio by plotting clay vs. fines.

NB: No new PSD data available for 'definitely' moderate K sites in Roscommon, Monaghan and Kilkenny. As with the BS review, it may also be useful, therefore, to identify clay % and fines % categories into which low K samples do NOT fall, rather than concentrating on categories into which mod K samples DO fall.

Results

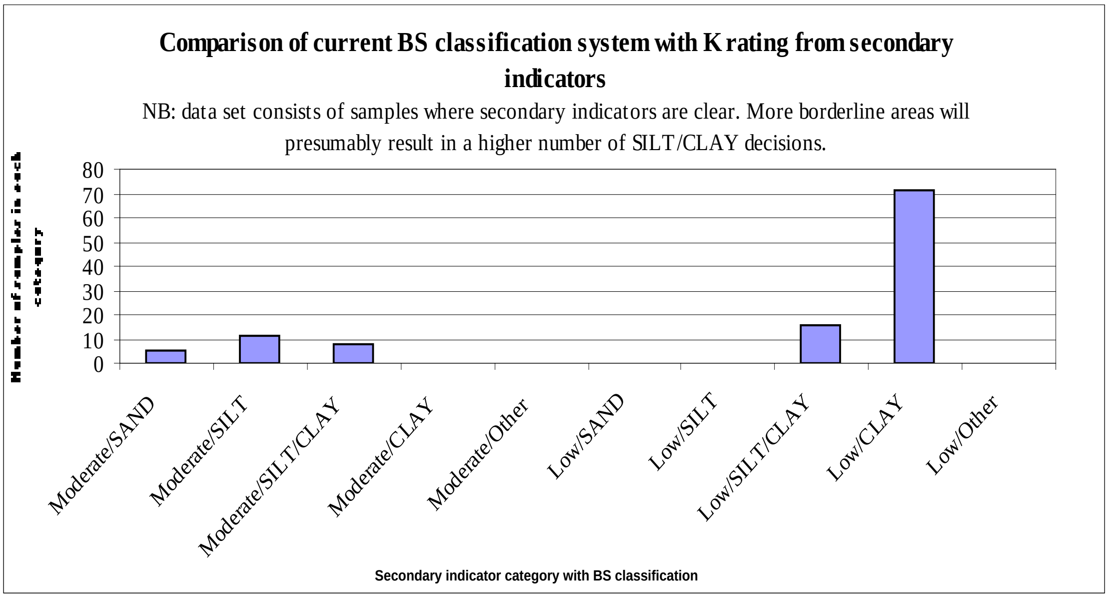
The % clay, where available, appears to give a much stronger boundary between mod K and low K than the % fines.

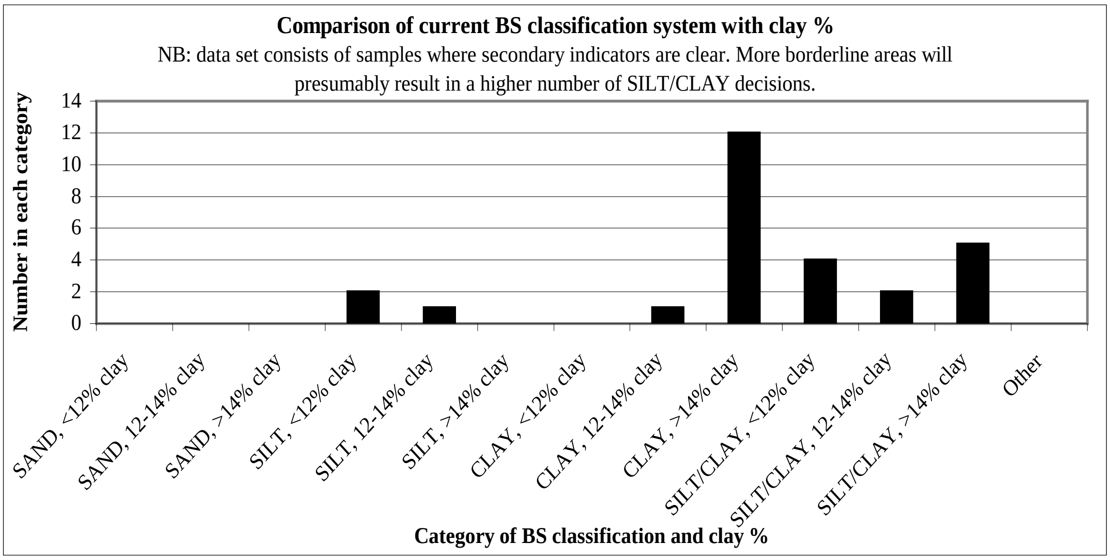
Low K.	95% results > 13% clay or > 37% fines
Mod K.	95% results < 14% clay or < 46% fines

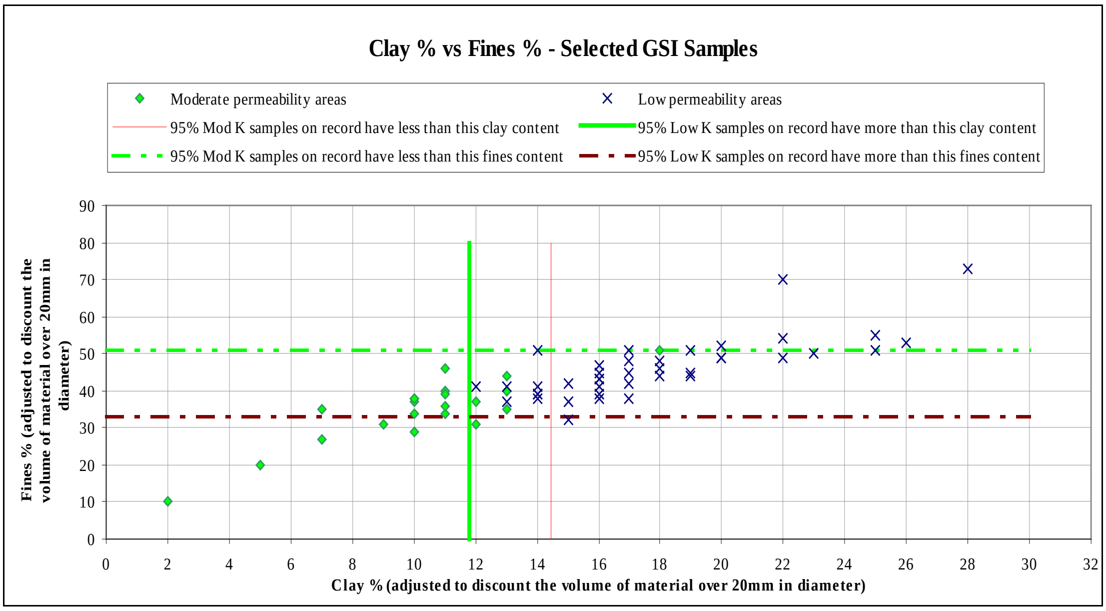
7.16 Recommendations

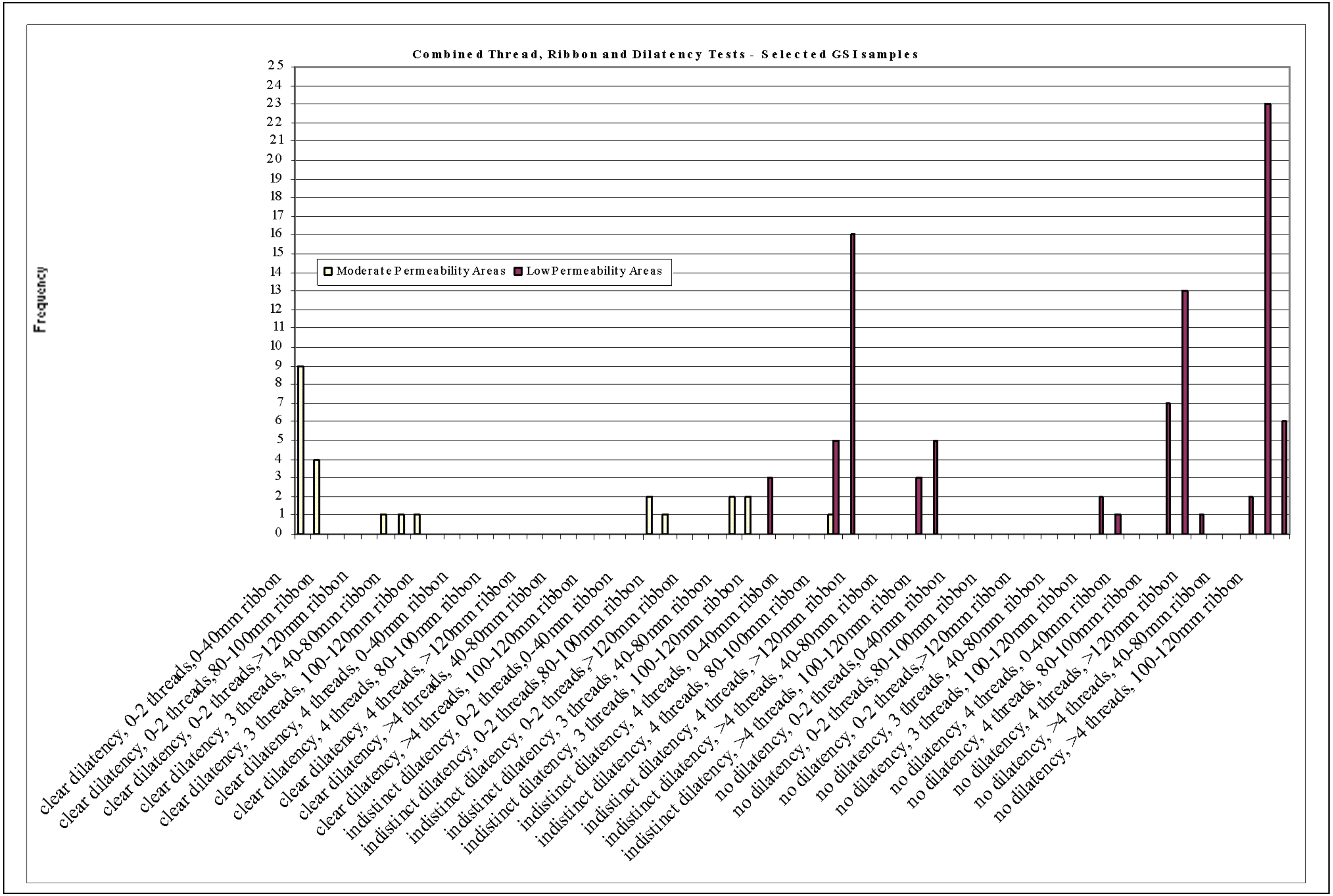
- Low permeability: Described as CLAY and >14% clay or > 50% fines by volume (corrected to remove particles over 20mm in diameter)
- Moderate permeability: Described as SILT or SAND and <12% clay or <35% fines by volume (corrected to remove particles over 20mm in diameter)
- If clay data is available, this should form the basis of any decision made using particle size data. If the clay % is between 12 and 14%, consider the fines data from the sample a little more closely. If it's >50% or <35%, it may help to refine your decision.

- If clay data is not available, fines % will obviously form the basis of any decision made using particle size data.
- Though the clay % appears to allow for more clarity in decision-making, it should be borne in mind that:
  - the fines % is very useful in its own right, and that
  - the PSD analysis including clay is roughly 3 times more expensive than the fines only analysis. Depending on the available budget, frequent clay analyses may not be economically viable.


Comparison of current BS classification system with K rating from secondary indicators
NB: data set consists of samples where secondary indicators are clear. More borderline areas will presumably result in a higher number of SILT/CLAY decisions.
Number of samples in each category
Moderate/SAND
Moderate/SILT
Moderate/SILT/CLAY
Moderate/CLAY
Moderate/Other
Low/SAND
Low/SILT
Low/SILT/CLAY
Low/CLAY
Low/Other
Secondary indicator category with BS classification


Comparison of current BS classification system with clay %
NB: data set consists of samples where secondary indicators are clear. More borderline areas will presumably result in a higher number of SILT/CLAY decisions.
Number in each category
SAND, <12% clay
SAND, 12-14% clay
SAND, >14% clay
SILT, <12% clay
SILT, 12-14% clay
SILT, >14% clay
CLAY, <12% clay
CLAY, 12-14% clay
CLAY, >14% clay
SILT/CLAY, <12% clay
SILT/CLAY, 12-14% clay
SILT/CLAY, >14% clay
Other
Category of BS classification and clay %


Clay % vs Fines % - Selected GSI Samples
Moderate permeability areas
Low permeability areas
95% Mod K samples on record have less than this clay content
95% Low K samples on record have more than this clay content
95% Mod K samples on record have less than this fines content
95% Low K samples on record have more than this fines content
Fines % (adjusted to discount the volume of material over 20mm in diameter)
Clay % (adjusted to discount the volume of material over 20mm in diameter)


Combined Thread, Ribbon and Dilatency Tests - Selected GSI samples
Frequency
Moderate Permeability Areas
Low Permeability Areas
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
clear dilatency, 0-2 threads,0-40mm ribbon
clear dilatency, 0-2 threads,80-100mm ribbon
clear dilatency, 0-2 threads,>120mm ribbon
clear dilatency, 3 threads, 40-80mm ribbon
clear dilatency, 3 threads, 100-120mm ribbon
clear dilatency, 4 threads, 0-40mm ribbon
clear dilatency, 4 threads, 80-100mm ribbon
clear dilatency, 4 threads, >120mm ribbon
clear dilatency, >4 threads, 40-80mm ribbon
indistinct dilatency, >4 threads, 100-120mm ribbon
indistinct dilatency, 0-2 threads,0-40mm ribbon
indistinct dilatency, 0-2 threads,80-100mm ribbon
indistinct dilatency, 0-2 threads>120mm ribbon
indistinct dilatency, 3 threads, 40-80mm ribbon
indistinct dilatency, 3 threads, 100-120mm ribbon
indistinct dilatency, 4 threads, 0-40mm ribbon
indistinct dilatency, 4 threads, 80-100mm ribbon
indistinct dilatency, 4 threads, >120mm ribbon
indistinct dilatency, >4 threads, 40-80mm ribbon
no dilatency, >4 threads, 100-120mm ribbon
no dilatency, 0-2 threads,0-40mm ribbon
no dilatency, 0-2 threads,80-100mm ribbon
no dilatency, 0-2 threads>120mm ribbon
no dilatency, 3 threads, 40-80mm ribbon
no dilatency, 3 threads, 100-120mm ribbon
no dilatency, 4 threads, 0-40mm ribbon
no dilatency, 4 threads, 80-100mm ribbon
no dilatency, 4 threads, >120mm ribbon
no dilatency, >4 threads, 40-80mm ribbon
no dilatency, >4 threads, 100-120mm ribbon