Review of the Performance of Hydraulically Contained Landfills

7 March 2001

Entec UK Limited

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Executive Summary

Background

This report presents the results of a research project carried out by Entec UK Ltd over the period 1999 to 2000 funded by E B Nationwide, through the landfill tax credit scheme. The aim of the project was to investigate the use and the success of hydraulic containment as a leachate control strategy in landfills in the UK. The project was primarily to collect data about the sites in the UK using this strategy and to present it as a research report. The work has involved a literature review of relevant legislation and guidance and of technical aspects of the approach, and a survey of hydraulically contained sites in the UK.

Hydraulic containment is the practice of operating a landfill where the base of the waste is below the water table and the level of the leachate in the waste is maintained at a level lower than that in the surrounding groundwater. Maintaining leachate levels below the potentiometric level of the groundwater creates a pressure gradient into the waste and since fluid cannot flow against a pressure gradient, ensures that leachate cannot leave the landfill.

Hydraulic containment, as a landfill strategy, is poorly understood. The application of the law by regulators and associated guidance available for operators tends to avoid the issue. Even operators are not always aware that the objective is to ensure leachate heads are kept well below groundwater heads.

Legislation and Literature Review

A review of the available legislation and guidance indicates that hydraulic containment may be permitted if the hydrogeological conditions are suitable and the engineering measures are acceptable. The suitability of the hydrogeological conditions includes seasonal and long-term variations in water levels. The engineering aspects include risks of hydraulic heave and other failure scenarios for the liner which could lead to direct discharges of List I substances through the failed liner to groundwater, and the sustainability of any long term groundwater abstraction.

It could be concluded from this literature review that hydraulically contained sites would be accepted if it could be demonstrated that the liner or liners could be emplaced without significant risk of failure, that long term groundwater abstraction was not necessary or was sustainable, and that leachate levels could be maintained safely below those in the surrounding strata for the lifetime of the site. It is noted that maintenance of leachate levels is a strict requirement of physically maintained sites.

Survey of UK Sites

Entec has gained as much information as possible, within the time scale constraints, about hydraulically contained landfills from a variety of sources including the Environment Agency, landfill operators and two database systems. This survey has found that:

- The identification of hydraulically contained sites has been difficult, in part due to operator's and County Council's lack of understanding of the issue or their sites, but also due to lack of co-operation from some Waste Contractors and local councils, and a nervousness in co-operation from the Environment Agency.

- Significant errors (accuracy has been estimated at 30%) have been identified in the Environment Agency's landfill database collated by WRc in 1994. The database is not publicly accessible and many of the errors may be due to incomplete or inaccurate information supplied to WRc when they undertook the survey. However, it is apparent that there is not an accurate record of the number of hydraulically contained sites in the UK and this report is likely to be the best estimate at this time.
- The survey suggests that there are at least 27 hydraulically contained sites within the UK and there are estimated to be as many as 40 to 50 in total.
- A significant number of the sites appear to be located in southern and eastern England, but there appears to be hydraulically contained sites within each Environment Agency Region of England and Wales.
- Many of the hydraulically contained sites are within lower permeability (non-aquifer) strata such as the Jurassic Clays and the Mercia Mudstone. This may, in part, explain the predominance of sites in southern and eastern England. There are however sites which are situated within sands and gravels and there is one in the Sherwood Sandstone. These formations are designated as Major Aquifers.
- The engineered containment system varies from no lining, 1 m of engineered clay as a basal liner and sometimes as a side-slope liner, to composite basal liners of HDPE over clay and HDPE over BES.
- Leachate levels vary in elevation above the base of each site and with respect to the potentiometric levels. Most of the sites operate on the basis of a fixed leachate level above the base of the site rather than below the local potentiometric level. This means that most of them appear to be assuming leachate leakage through the liner rather than minimising groundwater ingress through their operation. Leachate levels are typically no more than 10 m below the local potentiometric level, but four sites have leachate levels between 10 and 25 m below potentiometric levels and one site maintains a difference of between 25 and 49 m.
- The volumes of leachate extracted at a number of sites strongly indicates that groundwater ingress is occurring. The amount of ingress appears to be dependent on the difference between leachate levels and potentiometric levels, but also the hydraulic conductivity of the lining system or surrounding strata. The highest ingress equivalent to ~35 000 m^3/ha/a is however at a site with a HDPE over clay composite liner, but with no side wall lining in the Mercia Mudstone. This rate of ingress is considerably higher than could be expected for an uncapped site with say 3-400 mm/a effective rainfall (equivalent to 3-4 000 m^3/ha/a).
- The rate of groundwater ingress averaged across each of the sites appears to be of the order of 20 to 50 m^3/day and this is equivalent to only a small agricultural abstraction in terms of groundwater resources.
- Some of the sites have been in operation since the late 1970's, but there is no reported evidence of groundwater or surface water contamination around any of the sites.

Conclusions and Recommendations

Based on the literature review and the site survey, the main issues concerning hydraulically contained sites have been discussed and recommendations have been made for their assessment. This includes issues such as leachate control, groundwater risk assessment, waste stabilisation and sustainability.

Contents

Glossary

Above Water Table Landfills	A landfill where the base of the waste is above the maximum elevation of the water table and so normally has an underlying unsaturated zone (see also Section 2.2.1).
Accelerated Stabilisation	The achievement of a 'stable' condition as soon as possible ('stable' meaning that leachate is too dilute to cause any harm)
Aquiclude	Rock or soil with low permeability that inhibits groundwater flow
Aquifer	Permeable water-bearing rock or soil with significant water resource
Capillary Zone	In an unconfined aquifer, this is a zone of full saturation above the water table (as defined by the level of water in a hole). In practice it is only a few cm for sands, tens of cm for silts and sometimes over a metre for clays.
Cap Infiltration	The amount of water, normally derived from rainfall, that seaps through the landfills low permeability cap.
Direct discharge	"The introduction into groundwater of substances in lists I or II without percolation through the ground or subsoil" [quoted from EC Directive 80/68/EEC]
Dilute-and-Disperse	A landfill that is designed to leak leachate and relies on the dilution of the groundwater crossflow beneath to dilute any contaminants to beneath harmful levels
Flushing Bioreactor	An approach to landfill management that accelerates the dilution of leachate and biodegradation of source chemicals in the waste by enhancing the flow of water through the waste. This has the effect of maintaining saturation, removing waste products and introducing oxygen (and sometimes other chemicals necessary to maintain the degradation reactions)
Groundwater	"All water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil" [quoted from EC Directive 80/68/EEC]
Hydraulic containment	Containment that uses a reverse pressure gradient (i.e. water flow is entering the body of the waste)
Hydrostatic Heave	Failure of a low permeability liner system because the external groundwater pressure exceeds the weight of the liner, the waste emplaced and any leachate, pushing the liner system upwards

Indirect discharge	"The introduction into groundwater of substances in lists I or II after percolation through the ground or subsoil" [quoted from EC Directive 80/68/EEC]
Leachate	The liquid that results from the addition of water to waste
Liner	A low permeability layer enclosing waste in a landfill, used in this text to mean both mineral liners (e.g. clay) and artificial liners (e.g. geomembranes, bentonite enhanced sand)
Physical Containment	Design of landfill to contain the leachate (as opposed to dilute-and-disperse)
Pollution	"The discharge by man, directly or indirectly, of substances or energy into groundwater, the results of which are such as to endanger human health or water supplies, harm living resources and the aquatic ecosystem or interfere with other legitimate uses of water" [quoted from EC Directive 80/68/EEC]
Potentiometric Level	The level that represents the static head of groundwater in both confined aquifers and water table aquifers. This term includes piezometric level and water table.
Sorption	A collective term for adsorption and absorption. Adsorption is the process by which solutes attach to a surface, absorption occurs when solutes attach to surfaces within a the pores of individual particles.
Underdrainage Layer	A high permeability layer (usually of sand or gravel) placed beneath the main low permeability liner
Unsaturated Zone	That part of an aquifer between the ground surface and the water table.
Sub-Water Table Landfill	A landfill where the base of the waste is at some point in contact with, or below, the water table (see also Section 2.2.2).
Unsaturated Zone	The soil zone where there is a significant proportion of air occupying the soil porosity

1. Introduction

1.1 Introduction

Modern landfills are designed to minimise leachate impact on the environment. This is usually achieved through the use of low permeability barriers and leachate control systems, which reduce leakage to a minimum by ***physical containment***. An alternative, sometimes non-intended, design is ***hydraulic containment*** where leachate is prevented from leaving the landfill by maintaining a pressure gradient into the site from the surrounding groundwater.

By default, hydraulically contained sites are sub-water table, but not all ***sub-water table landfill*** sites may be hydraulically contained, i.e. leachate levels may be above the elevation of the surrounding water table. It is noted that both hydraulically contained sites and sub-water table sites are also usually physically contained.

Physical containment designs have developed significantly over the last five to ten years through the use of:

- lining systems; engineered mineral liners, bentonite enriched sand (BES), geosynthetic clay liners (GCL), asphaltic and dense asphaltic concrete (DAC) liners and composites of these with HDPE membrane liners;
- improved leachate control methods such as spine or herringbone drains, drainage blankets and retro-fit wells.

In contrast, the use of hydraulic containment as a landfill strategy is poorly documented and written experience with the strategy is hard to find. Furthermore, not all landfill operators are aware of the requirements for hydraulic containment and the potential advantages for landfill operation.

Perhaps due to the poor documentation and often non-deliberate use of hydraulic containment, Environmental regulators in the UK (the Environment Agency, Scottish Environment Protection Agency, and Environment and Heritage Services in Northern Ireland) appear to have a lack of confidence in the strategy of hydraulic containment. As an illustration of this, guidance issued by the regulators does not address the strategy in any detail (see Section 3).

The lack of information on hydraulic containment prevents a rational assessment of the potential success of the strategy. The work described in this report therefore represents an attempt to improve understanding of hydraulic containment in the UK so that future decisions on the use of this strategy are made with a better understanding than is currently available.

1.2 Project Funding

The research project was carried out by Entec UK Ltd over the period 1999 to 2000 with funding from E B Nationwide.

1.3 Objectives

The main objective of this project was to produce a reference document, which presents the available data and summarises the existing situation on hydraulic containment in the UK.

Specifically the objectives of the research project were to:

- Summarise the occurrence and approach to hydraulic containment in landfills in the UK, and detail the design and operational techniques in use;
- Collect monitoring data for a range of hydraulically contained sites;
- On the basis of monitoring data, assess the effectiveness of hydraulic containment as a strategy;
- Discuss the long-term performance, the legal aspects and potential loss of water resource caused by hydraulic containment.

These objectives were set, with little available information on hydraulic containment in the UK. Despite considerable efforts being made to collate and assess the information reported here, the research has revealed that the level of understanding of hydraulic containment, and the quantity of available information is significantly more limited than had been hoped.

The relatively limited information has prevented detailed assessment of the effectiveness of hydraulic containment, and recommendations are made for an additional project to collect and assess the necessary information. In addition, the work required a considerable degree of co-operation from Environmental Regulators and landfill operators. Entec is grateful for that co-operation received, but it is noted that co-operation was not always given, and so many unknowns regarding the number of sites and the availability of monitoring data remain.

1.4 Methodology

The approach of this project was first to undertake a review of the available literature on hydraulic containment including consideration of the pertinent legislation and guidance.

Following the literature review, an attempt was then made to identify hydraulically contained sites from existing information sources, including databases, environmental regulators and landfill operators. This was backed up with an initial questionnaire, the aim of which was also to identify hydraulically contained sites. Once a number of hydraulically contained sites had been identified, these were then subject to a more detailed data gathering exercise (using a second questionnaire) to assess the available data and performance.

1.5 Layout of this Report

Following this introductory section, background information is given in Section 2 providing descriptions of the different types of landfill site and the main issues affecting landfill design related to hydraulic containment. Against this background, the literature review of legislation and guidance is provided in Section 3, and Section 4 summarises the technical findings of the literature review.

The results of the search for sites are presented in Section 5. The two questionnaires are provided in Appendix A and B and details of identified sites are provided in Appendix C.

The key findings of the project are summarised in Section 7.

1.6 Definitions

All terms in ***italics*** in this document are defined in the glossary after the contents page. After the first use of the word italics are not used again. Key definitions are discussed in more detail in Section 2.

1.7 Acknowledgements

Entec acknowledge the assistance and co-operation of a number of landfill operators and Environment Agency staff in the data collection for this project. We would like to thank all the operators who responded to our inquiries (including those with no relevant sites). In particular the following operators provided important assistance: Shanks, RMC, Viridor, Wastewise, Wyvern Waste, Cory, Cleanaway, Hanson Waste, Bucbricks Ltd, Thames Waste, LincWaste, Landfill Management, Grundon, and Yorwaste.

2. Types of Landfills and Issues

2.1 Introduction

This section provides some background information on the types of landfill and the issues that affect their design. This helps to provide clarity and greater understanding of the subsequent sections.

2.2 Types of Landfills

Landfills can be divided broadly into two categories, depending upon the relative position of the water table (or potentiometric level) and the base of the landfill site. These categories are "***above water table landfills***" and "***sub-water table landfills***". Hydraulically contained sites are a subset of the second category of landfill, the subdivision depending upon the relative position of level of leachate within the site with respect to the water table. Definitions and characteristics of these landfill types are given below.

2.2.1 Above Water Table Landfills

Above water table landfills sit with their base above the maximum elevation of the water table (or piezometric level) at all times. In this situation there is always an unsaturated zone beneath the base of the landfill. The unsaturated zone can range in thickness from fractions of a metre to many tens of metres. A minimum thickness for the unsaturated zone is not a feature of the definition.

A schematic illustration of an above water table landfill is given on Figure 2.1.

Leachate is typically retained within the landfill by a low permeability liner. Since the early 1990's, there have been significant developments in producing single or composite liners with the potential to limit leakage. However, as all liners have the potential to leak no matter how low their permeability, there will always be some leachate release through the base of even the most highly engineered landfill. Once through the bottom of the liner, leachate will travel via the unsaturated zone to the saturated zone.

2.2.2 Sub Water Table Landfills

Landfills which have no unsaturated zone beneath them because the base of the waste is below the maximum elevation of the water table are ***sub-water table landfills***. In areas where the water table fluctuates over time, due to seasonal, or other effects, landfills may be sub-water table for only part of the time, but are included in this category (Figure 2.2).

In the absence of a liner, a sub-water table landfill will be, in most cases, an unsatisfactory landfill solution, since the leachate and the groundwater can freely mix within the waste body and be transported off site in the down-gradient direction.

Sub-water table landfills have often been constructed in this way because the excavation used was already at a lower level than the water table and the void space was available. On older landfills, landfilling may have commenced before the current regulatory framework was in place. However, some landfills are deliberately designed as sub-water table to maximise void space and to gain benefit from an established waste management infrastructure.

2.2.3 Hydraulically Contained Landfills

Hydraulic containment refers to the practice of landfilling where the base of the waste is below the water table and the level of the leachate in the waste is maintained at a level lower than the minimum level of the surrounding groundwater. This creates a pressure gradient into the waste at all times and since fluid cannot flow against a pressure gradient, ensures that leachate cannot leak from the landfill. This leaves ***diffusion*** as the only possible transport mechanism for contaminants to migrate from the waste.

Hydraulic containment also requires the base of the landfill to be far enough below the water table to accommodate seasonal fluctuations in the water table to ensure that there is a reliable and adequate pressure gradient into the landfill at all times.

Hydraulic containment sites do not require a low permeability liner to function, but a liner could generally be installed for two main reasons:

i) To engineer a site below the water table often requires that groundwater lowering is used to give access. The groundwater lowering is only finished once landfilling has been completed, to prevent heave of the liner. Thus the landfill starts life as an above water table landfill and physical containment is required to protect against leachate migration.

ii) A low permeability liner reduces groundwater inflows to the site and thus the quantity of leachate required to be pumped and treated to maintain head differences. Without the liner, the quantities of leachate pumped out to maintain a reasonable head difference could be large where the landfill is situated in a permeable formation. Large inflows to the site could also impact water resources in the surrounding strata.

A third reason may be to reduce the diffusional flux of contaminants out of the site.

The most suitable landfills for hydraulic containment are landfills that penetrate several metres, below the water table. For a typical Waste Management Licence (now PPC Permit) that requires the operator to keep leachate levels at one or two metres above the base of the landfill, then there is a safety margin to cover uncertainties about leachate levels between monitoring points and to cover what <u>might</u> happen to leachate levels during wet conditions.

Unless leachate levels can be permanently maintained below the water table everywhere in the site, then the site should not be considered as a hydraulically contained landfill. Sites that have fluctuating groundwater tables which result in intermittent hydraulic containment may not meet the requirements of the Groundwater Directive with respect to direct discharges of List I substances. As groundwater levels intersect the base of the landfill there will be no unsaturated zone and therefore leachate leakage would technically form a direct discharge to groundwater.

Landfills, that are for instance, <u>seasonally</u> sub-water table are not suitable for hydraulic containment, because when the water table falls below the base of the waste, they are no longer hydraulically contained. Figure 2.2 shows a schematic section through a seasonally sub-water table landfill.

2.2.4 Water-Table-Lowering Landfills

A different, but related approach to, hydraulic containment, is water table lowering to artificially create an unsaturated zone beneath a landfill. Water table lowering is achieved by pumping groundwater from boreholes or sumps around the landfill, sometimes in combination with a high permeability ***underdrainage layer*** immediately beneath the landfill liner. Figure 2.3 illustrates the concept of water table lowering beneath a landfill.

For most sub-water table landfills, water table lowering is generally necessary on a temporary basis to permit installation of the liner in dry conditions and to prevent hydraulic heave of the liner before it is loaded with waste. A suitable dewatering system is often already in place from mineral extraction activity at the same site.

Maintaining an unsaturated zone by water table lowering has the benefits, described in Section 2.2.1, of creating additional attenuation potential within the unsaturated zone, but has the disadvantage that pumping has to be continued until the waste has stabilised. It is likely to involve considerably more pumping than a lined hydraulic containment landfill although disposal of the uncontaminated groundwater that will be abstracted is likely to be easier and cheaper (per unit volume) than disposal of leachate. The higher volume of pumping arises because, firstly, there is no barrier containing the groundwater (i.e. it may be connected to a virtually limitless reservoir) and secondly, the permeability of natural ground is often much higher than that of compacted waste. The consumption of energy in the pumping large volumes of groundwater will result in additional long-term operational costs.

2.2.5 Combination Landfills

The three categories of landfill described in this section represent part of a spectrum of different landfill types. Even within a single site, some parts could be above the water table, whilst others are sub-water table or even hydraulically contained. Even a single cell can be hydraulically contained at one boundary, and sub-water table at another, as a result of the fall in the water table or cell base across a site (Figure 2.2).

2.3 Issues that Affect Landfill Design and Operation

The concept of hydraulic containment raises a number of issues. A brief discussion of these issues is given here. In Section 5, site specific data are provided to address a number of these issues.

2.3.1 Size of Landfill Site

Larger landfill sites, i.e. sites with a large void, are generally regarded as beneficial both to operators (for reasons of cost) and the environment as a whole. It is becoming increasingly more difficult to find and subsequently obtain planning permission for new sites and, even with the successful waste minimisation policies now being pursued, large volumes of waste will still need to be disposed of by landfill. Deep landfills maximise the volume of waste disposal capacity for a given land take. However, many of the deeper landfills extend below the water table.

2.3.2 Physical Containment

All landfills, even capped sites, produce a certain amount of leachate, which may contain polluting substances. In above water table landfills, methods of minimising leachate contamination of groundwater beneath the site typically involve engineered lining systems placed beneath and around the waste (***physical containment***). Such lining systems typically consist of a mineral liner such as a low permeability clay, Bentonite Enhanced Soil (BES) or Geosynthetic Clay Liner (GCL). Other lining systems include asphalt and dense asphaltic concrete (DAC). Some of these liners are often overlain by a geomembrane such as high density polyethylene (HDPE) to form a composite lining system.

Clay liners typically have maximum specified hydraulic conductivities of 1×10^{-9} m/s. In addition to their hydraulic properties mineral liners can permit ***sorption*** of many common leachate contaminants (ammonium, heavy metals and organic compounds). Geomembranes have much lower hydraulic conductivities ($\sim 10^{-12}$ to 10^{-14} m/s) than mineral liners but have no attenuating capacity and can easily be punctured. Composite liners combine the low hydraulic conductivity of the geomembrane with the attenuating properties of the underlying clay. In addition, a mineral liner beneath a HDPE geomembrane ensures that any punctures in the geomembrane do not lead to catastrophic failure of the lining system.

2.3.3 Mechanisms of Liner Failure

Liners, both mineral and geomembrane, can fail for various reasons. Most authors (e.g. Tammemagi, 1999) list the following:

- formation of cracks by drying or freeze/thaw processes;
- penetration of liner by roots or burrowing animals;
- differential settlement of waste;
- gas penetration;
- changes in chemistry of leachate or pore-water*;
- accidental damage.

Note: *A number of authors have shown that some chemicals (e.g. chlorinated solvents) that may be present in some leachates can have a detrimental effect on the permeability of clay liners (e.g. Brown, Anderson (date unknown) and Monserrate, 1982).

Hydraulic containment has some advantages in that:

- the mineral liner is kept moist, preventing desiccation cracks from forming;
- burrowing by animals seems unlikely (!); and
- the water permeating the mineral liner is groundwater from the outside rather than leachate from the inside and so is more likely to be compatible with the liner's original pore water than leachate.

However, overall the principal advantage of hydraulic containment over other forms of landfill is that leachate is unable to escape even in the event of the liner failing. The main implication for liner failure for these sites is increased leachate generation and some loss of water resource due to increased groundwater ingress into the site. The liner performance is therefore not integral to the system performance in terms of groundwater protection.

2.3.4 Liner Leakage and Groundwater Pollution

It is generally accepted that above water table landfills leak to some extent through their base. For example, the DETR approved landfill simulation model LandSim (DOE, 1996) closely examines the different aspects of a site's leachate drainage system and liner to determine liner leakage.

As some leakage occurs, a change in the quality of the underlying groundwater is inevitable due to the movement of conservative contaminants such as chloride and, where attenuation is inadequate, by other contaminants such as ammonia, metals and trace organics.

In hydraulically contained landfills there should be no leakage of leachate and therefore no potential for groundwater contamination by leachate migration out of the site. The only mechanism for contamination of groundwater is where the diffusion of contaminants from the leachate through the liner into the enclosing strata is greater than the rate of flow into the site.

2.3.5 The Role of the Unsaturated Zone

The presence of a substantial unsaturated zone beneath a landfill, in addition to a low permeability barrier, permits contaminants in the leachate to be retarded (sorption, cation exchange, precipitation etc.) on route to the water table. As well as providing additional retardation beneath the liner, volatilisation and aerobic biodegradation and oxidation can also occur in the unsaturated zone and this can reduce concentrations of some contaminants significantly. However, at some sites, the unsaturated zone could be thin and the attenuation capabilities limited or overwhelmed.

The chemical and biological processes occurring in the unsaturated zone are still not fully understood. Research continues into the attenuating processes (including sorption, biodegradation and oxidation), how they vary between different soils and whether they will change with the passage of time (for example, as the oxygen is 'used up').

2.3.6 Risk Assessment

The potential for all landfill sites to contaminate underlying groundwater is assessed for all non-inert landfill sites through a groundwater risk assessment. This is a requirement of the Groundwater Directive (see Section 3) as enforced in England and Wales through Regulation 15 of the Waste Management Licensing Regulations (1994) and more recently through the PPC Regulations (2000). The results of these assessments should feed back into the landfill design.

For above water table and sub water table landfills (excluding hydraulically contained sites) a significant part of these risk assessments is estimation of the leakage through the site's liner into the underlying strata. As outward liner leakage should not occur at correctly operated hydraulically contained sites, this risk does not exist. Environmental regulators are unlikely to accept that a risk assessment is not carried out on this basis, but yet the methods to be used for such a risk assessment are a subject for debate. One option is that the risk assessment needs to consider the net outcome of diffusional movement of contaminants outwards and groundwater flow into the site.

2.3.7 Waste Stabilisation

Waste degradation requires moisture and the ultimate stabilisation of a landfill, at which point the leachate and waste poses no significant threat to the water environment, requires flushing of water (Knox 1996).

The practice of surrounding waste with low permeability liners and a cap (dry entombment), as a landfill strategy is now considered by both regulators and operators as unsatisfactory and unsustainable. With dry entombment, waste is stored in a dry condition with no fluid movement, and so it does not biodegrade. Should the liner or cap or both fail in the distant future (possibly several hundred to thousands of years hence), infiltration or groundwater will enter the landfill and degradation processes will be reactivated producing high-strength leachate.

As stated in Waste Management Paper 26B: "Isolation of the waste from the environment is not compatible with the long-term aim of sustainable development because the potential hazards do not decrease with time." In Waste Management Paper 26B, the dry entombment philosophy is explained in detail and the case is made for *accelerated stabilisation*, whereby degradation of waste is encouraged by increasing the flow of water through the waste pile, for example by leachate recirculation.

The accelerated stabilisation approach has been extended to encompass the concept of deliberately adding large volumes of liquid to the waste to enhance the speed of stabilisation known as the *flushing bioreactor*. Normally, addition of water is from the top of the waste and whilst it has been shown (Knox, 1996) that there is an increase in the amount of water passing through the waste, a lot of the added water appears to by-pass the waste and move directly to the landfill liner.

Hydraulic containment may help with the stabilisation of waste as a result of the higher volumes of liquid flushed through the waste due to groundwater ingress. Strategies to maximise flushing efficiency might include extracting leachate from the top of the saturated zone, to pull groundwater through the saturated waste, rather than pumping from the base of the landfill and effectively abstracting groundwater.

The use of hydraulic containment may lead to much larger volumes of waste being permanently saturated when compared to above-the-water-table landfills. The impact of saturation on the rate of stabilisation of waste is poorly understood.

2.3.8 Leachate Extraction

For the vast majority of landfill sites, there will be a need to control leachate levels and so leachate extraction is needed. In the early stages of these landfill's infilling, recirculation of treated leachate from wet areas to dry areas may obviate the need to export leachate from the site, but eventually leachate extraction will be required.

The only sites where leachate extraction is not required would be where the cap infiltration and liner leakage were similar and that the liner leakage did not cause pollution of underlying groundwater.

If it is accepted that waste stabilisation (see Section 2.3.7) requires a certain amount of flushing through the waste, then regardless of whether the water for flushing is derived from cap infiltration or groundwater ingress, a similar amount of leachate extraction will be needed for all sites over their lifespan. Non hydraulically contained landfill sites may need slightly more leachate extraction than at other sites, as no leachate is lost through the liner. It is debatable whether this loss through the liner is better for the environment than controlled extraction and treatment.

2.3.9 Water Resources

In an above the water table landfill, there is generally little loss of water resource except the loss of the cap infiltration into the waste. Where these sites are inadequately designed and/or operated, contamination of groundwater may lead to the loss of water resource.

Hydraulically contained landfills will draw some groundwater into the landfill as a result of the pressure gradient created. Once inside the landfill groundwater becomes leachate and is lost as a resource. In a permeable formation, hydraulic containment of an unlined landfill could result in the need to abstract large volumes of groundwater and a substantial loss of resource. The loss of resource can be minimised by limiting groundwater ingress through the use of a low permeability liner.

Water table lowering landfills by definition have groundwater abstraction from beneath the site. In permeable formations, this abstraction could be significant.

3. Legislation and Guidance

3.1 Introduction

This section summarises the findings of the literature review with respect to legislation and guidance pertaining to hydraulically contained landfill sites and protection of groundwater.

The Environment Agency exercises its duties of groundwater protection with respect to landfills via two specific mechanisms:

i) the requirement that the Agency is consulted over all planning permission applications (which includes landfills);

ii) the requirement for a groundwater risk assessment for a landfill permit application (and every four years for existing permit holders) formerly under Regulation 15 of the **Waste Management Licensing Regulations 1994 (SI 1056)** and now under the **PPC Regulations (2000).** These regulations enforce the EU Groundwater Directive (80/68/EEC) which aims at controlling the discharge of specified substances to groundwater.

These mechanisms are discussed in more detail in the subsections below.

3.2 Planning Policy

The Environment Agency is a statutory consultee for all development planning applications under the **Town & Country Planning Act (1990)**. The main guidance for applicants issued by the Agency is contained in the document, **Policy and Practice for the Protection of Groundwater** (Environment Agency, 1998).

According to this document (Section C.6, p33):

> **"C.6 The Environment Agency will normally object to waste disposal activities, which extend to or below the water table in Source Protection Zones. Elsewhere the presence of an unsaturated zone will normally be required but a landfill operated on containment principles may be considered on a site-specific basis.**
>
> Wastes deposited below the water table will quickly generate leachate if groundwater ingress is not impeded. This may present operational difficulties and lead to rapid contamination of groundwater. The presence of an unsaturated zone gives an opportunity for attenuation to occur and leads to a delay in any impact on the water environment. The engineering of quarries excavated significantly below the water table will be difficult and expensive to achieve successfully in permeable strata. In such cases the Agency is likely to object to the deposition of potentially polluting wastes below the water table unless the hydrogeological conditions are suitable and the engineering measures are considered effective.**"**

In the above text, "Source Protection Zones" are designated areas around important groundwater abstractions as delineated by the Environment Agency. These are divided into an inner protection zone (Zone 1) equivalent to a travel-time of 50 days, an outer protection zone (Zone 2) equivalent to a 400 day travel-time, or 25% of the total catchment, whichever is largest. The area contributing recharge to the abstraction is the Total Catchment Zone (Zone 3). Large areas of both major and minor aquifers are covered by these zones and therefore lie within a source protection zone.

The second paragraph of PPPG (1998) Section C.6 above is not very helpful since it implies that the Agency may permit applications for hydraulic containment if "the hydrogeological conditions are suitable and the engineering measures are considered effective" but makes no further comments as to what is meant by "suitable" conditions or "effective" measures.

3.3 PPC Permits and Waste Management Licensing

3.3.1 Legislative Framework for Landfills

In addition to a landfill site gaining planning permission, to operate the site, the site operator needs a PPC Permit (formerly a waste management licence). It is often at this stage, that the final details of the landfill's design and operation are formally agreed between the site operator and the Environmental Regulator.

In agreeing the PPC Permit the Agency has to take into account its regulatory responsibilities, and with respect to groundwater protection, this means enforcing the requirements of the Groundwater Directive (80/68/EEC) through its transposition into UK Law. The main requirements of the Directive are that any activity with the potential to discharge List I or II substances to groundwater must be subject to "prior investigation" and the "requisite surveillance of groundwater".

The Groundwater Directive identifies List I and List II substances as groups of compounds, rather than individual compounds. No definite list of List I substances exists to date. Leachates from sites receiving household waste typically have high concentrations of ammonia (a List II substance), some of the heavy metals at lower concentrations (also List II), and, at much lower concentrations, some of the List I substances have been identified in leachate (Robinson, 1996; Knox *et al*, 2000).

Until August 2000, the requirements of the Groundwater Directive were enforced within the **Waste Management Licensing Regulations 1994 (SI 1056)**. Specifically, Regulation 15 enforced the "prior investigation" requirement. Since August 2000, the requirements are covered within the **PPC Regulations (2000)**.

3.3.2 Groundwater Regulations 1998

The principle of hydraulically contained landfill sites was the subject of a Public Inquiry relating to Round 'O' Quarry, Lancashire (Planning Inspectorate, 1998). The Inquiry arose as a result of the refusal of a Planning Application for a hydraulically contained landfill.

The Inspector in the Round 'O' Quarry Inquiry had to consider whether a hydraulically contained landfill would breach the obligations under the Groundwater Regulations (1998), as enacted in Regulation 15 of the Waste Management Licensing Regulations (1994), because it may be considered to constitute a direct discharge of List I substances to groundwater. The issue was whether groundwater entering a subwater table landfill represented contamination of groundwater as it became leachate within the landfill.

The Inspector, supported by the Environment Agency, considered that "groundwater entering the landfill containment ceases to be groundwater on crossing the barrier and, thereafter, immediately assumes the identity of leachate." The proposed hydraulically contained landfill was therefore found not to breach the Groundwater Regulations (1998).

3.3.3 Interpretation of Regulatory Requirements

The requirements for 'prior investigation' and requisite surveillance' are not clearly set out in the legislation but prior investigation must examine "the risk of pollution and alteration of the quality of the groundwater from the discharge and must establish whether the discharge of substances into the groundwater is a satisfactory solution from the point of view of the environment."

For a licence to be issued the Agency must be satisfied that:

- "the observance of all technical precautions necessary to prevent any discharges into groundwater of substances in List I".
- "the observance of all technical precautions for preventing groundwater pollution by substances in List II".

These requirements do not appear to preclude the concept of hydraulic containment which is a technical measure designed to achieve these objectives.

The lack of unsaturated zone in non hydraulically contained sub-water table landfills means that the discharge from the base of the landfill's liner is generally classified as *direct* rather than *indirect*. This means that if concentrations of List I substances are significant (i.e. in excess of detection levels or background levels) at the base of the landfill liner, then the site's activities would not meet the requirements of the Groundwater Directive.

3.3.4 Waste Management Paper 26B (1995)

Guidance produced by the DOE (now DETR) in 1995 in the form of **Waste Management Paper 26B**, 'Landfill Design, Construction and Operational Practice' is used by the Agency as guidance in assessing landfill designs. It is understood that the content of WMP 26B is currently being revised by the Environment Agency. WMP 26B makes only a brief reference to sub-water table landfills. Section 6.43 of WMP 26B makes the following remarks:

> **"**In those sites which are located below the water table, it will be necessary to relieve hydrostatic pressures which might otherwise give rise to uplifting forces on the site liner and lead to potential instability. In such cases an under drainage system will be required. Pumping of groundwater following completion of the landfill is not compatible with the aims of sustainable development and gravity drainage is preferred for all long-term requirements.
>
> Landfill constructed below the groundwater table can cause direct discharge to groundwater if the liner or leachate management system fails. Annual analysis

of leachate for List I and II substances at the point of discharge should be undertaken in such situations."

The guidance in WMP 26B makes no specific reference to hydraulically contained landfill sites. Indirect reference is made to operating sites on the principle of hydraulic containment by stating that long term dewatering is not considered sustainable. It can be deduced from this that the Environment Agency would expect to see groundwater being allowed to recover following completion of the site. No reference is made to how leachate levels should be managed once groundwater pumping ceases.

3.3.5 Environment Agency Internal Guidance (1999)

The Environment Agency's **Internal Guidance on the Interpretation and Application of Regulation 15** (Environment Agency, 1999) makes the following specific reference to sub-water table and hydraulically contained sites:

> **"**Those sites with a base below the local groundwater level and which have a potential for groundwater ingress should be treated as having the potential for direct discharges. Whereas in the short term or in one part of the site the hydraulic or chemical conditions may prevent a discharge to groundwater, in the long term or elsewhere in the site conditions may be different such that there is a gradient out of the site. The long term relative hydraulic conditions within and outside the site must be taken into consideration, together with the sustainability of any artificial controls on these conditions. In addition, there needs to be consideration of the nature of the landfill liner, as noted in Section 4.
>
> Groundwater levels can fluctuate, particularly with seasonal variations. Where this results in the groundwater alternating between levels that lie above and below the base of a site, or where groundwater ingress into the site occurs on a seasonal basis, potential discharges should be treated for the purpose of Regulations 15 as being direct.
>
> In locations where the water table is artificially depressed through pumping, consideration should be given to the possibility of rebound occurring during the biologically and/or chemically active life of the site; this will be a site-specific assessment. If the area has a long history of mineral extraction and there are no accurate data on past rest levels, the advice of a groundwater expert should be sought. Where it is anticipated that the water table will rebound above the level of the base of the site, the licence should be drafted and/or reviewed on the basis that any discharges may at some time in the future become direct.**"**

The Guidance acknowledges that hydraulic containment may prevent discharges in the short term but emphasises the need to consider the long term situation. The second paragraph quoted above deals with the seasonal sub-water table landfill. The final paragraph quoted above discusses the artificially lowered water table situation mentioned in Section 4.

3.4 Overview

The available legislation and guidance regarding hydraulically contained sites is not prescriptive, but the key points for consideration are as follows:

- **PPPG (1998)** Section C.6 implies that the Agency may permit applications for hydraulic containment if "the hydrogeological conditions are suitable and the engineering measures are considered effective".

- **Circular 11/94: Framework Directive on Waste** (Department of the Environment, 1994) indicated that direct discharges might arise where groundwater is allowed to enter the body of waste in the landfill. However, the inspector at the Round 'O' Quarry, Lancashire Public Inquiry (Planning Inspectorate, 1998) supported by the Environment Agency, considered that "groundwater entering the landfill containment ceases to be groundwater on crossing the barrier and, thereafter, immediately assumes the identity of leachate." This means that there is test case acceptance that fully hydraulically contained sites do not contravene the Groundwater Directive in terms of direct discharge of List I substances to groundwater.

- **Waste Management Paper 26 B** indicates that sites constructed below the water table should consider hydraulic heave of the liner during construction and that long term pumping of groundwater is not compatible with sustainable development. This guidance also notes that sub-water table landfill sites have the potential to cause a direct discharge to groundwater where the liner or leachate management system fails.

- The Environment Agency's **Internal Guidance on the Interpretation and Application of Regulation 15** (Environment Agency, 1999) re-visits the potential for direct discharges from landfill sites which are sub-water table and which have the potential for groundwater ingress (so hydraulically contained). It also flags up the issues of seasonally sub-water table sites and of the unsustainability of long term pumping.

The available legislation and guidance indicates that hydraulic containment may be permitted if the hydrogeological conditions are suitable and the engineering measures are acceptable. The suitability of the hydrogeological conditions includes seasonal and long term variations in water levels. The engineering aspects include risks of hydraulic heave and other failure scenarios for the liner which could lead to direct discharges of List I substances through the failed liner to groundwater, and the sustainability of any long term groundwater abstraction.

It could be concluded from the above that hydraulically contained sites would be accepted if it could be demonstrated that the liner or liners could be emplaced without significant risk of failure, that long term groundwater abstraction was not necessary or was sustainable, and that leachate levels could be maintained safely below those in the surrounding strata for the lifetime of the site. It is noted that maintenance of leachate levels is a strict requirement of physically maintained sites.

4. Review of Existing Information

4.1 Literature Review

4.1.1 Introduction

A literature and internet search for references to hydraulic containment as a landfill strategy was undertaken. The principal finding of the review was that references to hydraulic containment in the literature are rare. Those works that refer to hydraulic containment are reviewed in this section.

4.1.2 Principles of Hydraulic Containment

Smart (1993)

The principle of hydraulic containment for landfills is discussed in broad terms by Smart (1993). Smart (1993) recommends hydraulic containment in low permeability strata as an option with reduced potential for adverse effects on groundwater quality. The method does not necessitate "the development of a sophisticated engineering design with the associated costs". He mentions that hydraulic containment is particularly suited to:

- Former sand and gravel workings where there is a shallow unsaturated zone;
- Hard rock quarries excavated in strata designated as minor aquifers or non-aquifers (e.g. Coal Measures, Millstone Grit, clays and most igneous rocks).

Smart (1993) also discusses in detail some of the practical difficulties of constructing a landfill below the water table with reference to both dewatering during construction and leachate collection systems.

Fetter (1994)

Hydraulic containment is discussed in the textbook, *Applied Hydrogeology*, (Fetter, 1994). Fetter (1994) uses a different terminology, referring to hydraulically-contained landfills as "zone-of-saturation" landfills. The method is recommended for soils with hydraulic conductivities of 10^{-8} m/s or less. Fetter (1994) adds "The zone of saturation landfill is more efficient than the lined [above-the-water-table] landfill because no leachate escapes. However it will be necessary to collect the leachate long after the landfill is closed because the waste will be below the water table."

Fetter (1994) also describes the use of external groundwater control to lower the water table beneath the waste (as described in Section 4) to create an unsaturated zone beneath the landfill. He suggests an under-drainage system beneath the liner and calls this method "hydraulic-gradient-control."

4.1.3 Hydraulic Containment Designs

In addition to the construction of hydraulically contained sites in low permeability strata recommended by Smart (1993) and Fetter (1994), the review identified a number of other more novel hydraulic containment designs. These are summarised in the following subsections.

Sallfors and Peirce (1984)

Sallfors and Peirce (1984) proposed a variant on the hydraulic barrier approach ('the reverse flow landfill') whereby a second clay layer and a high permeability layer are placed beneath the principal landfill liner (two clay layers 'sandwiching' a sand layer). Water is then pumped through along this sand layer (see Figure 3.1). According to the authors, their proposed design:

- maintains hydraulic containment;
- avoids desiccation of the liner or chemical degradation since leachate will not come in contact with it.

The approach of Sallfors and Peirce (1984) is complex because it requires two clay layers enclosing a sand layer in addition to any drainage layer at the base of the waste. The authors suggest the use of a header tank with an elevation above the level of the leachate and a receiving tank on the other side of the landfill. They also note that a sand layer could be placed over the waste as well as underneath it, completely enclosing the waste with hydraulic barriers. It is not known whether this theoretical approach has ever been used in a landfill.

In theory, Sallfors and Peirce's design could be constructed within permeable as well as low permeable strata.

Lowry and Chan (1994)

Lowry and Chan (1994) discuss a method of landfill construction which is a simpler variation of that proposed by Sallfors and Peirce (1984). In this case, the high permeability layer is placed beneath the main landfill liner, but on top of the presumably low permeability in situ strata, and a hydraulic barrier is created by pumping water into this layer. A positive pressure is maintained that prevents the leachate from migrating outwards (see Figure 3.1). The method has been applied to a landfill in Ontario, Canada.

Rowe (1994)

Rowe (1994) discusses another complicated version of hydraulic containment (involving two liners sandwiching a hydraulic control layer) with various different pressure regimes. Rowe ran several scenarios on a calculation model (including a version of the Sallfors & Peirce design). The model of Rowe (1994) takes account of contaminant transport including dispersion and diffusion and appears to demonstrate that the long-term impact of diffusion and dispersion up-gradient (i.e. against the flow direction) is not negligible. The model is able to derive non-zero predictions of impact on receiving groundwater for hydraulic containment, unlike most risk assessment formulations in which the equations break down if the gradient is negative.

4.2 Current Research in the UK

The Environment Agency has commissioned an independent research **Project No P2-173 - Sustainable Engineering of Landfills Below the Water Table**. The project, which is being carried out by Enviros Aspinwall & Co Ltd, commenced in 1999 and is ongoing.

The overall objective of the project is "to produce practical guidance for Environment Agency staff and relevant stakeholders on the implications for groundwater protection from the disposal of waste in landfills below the water table, in order to facilitate informed policy development, consistent regulation and promotion of environmentally sustainable waste disposal practices".

The five specific objectives listed in the project brief were:

i) to review existing guidance, legislation and experience of sub-water table landfilling;

ii) analyse the likely hydraulic conditions around a sub-water table landfill over the full length of its lifetime in order to understand the risks to groundwater;

iii) develop guidance for operators and regulators covering the subjects of location of landfill, engineering and management – in order to achieve sustainable development within the legal framework;

iv) develop quantifiable indicators of sustainability;

v) identify further research.

The project is to focus on the detailed engineering and management of hydraulically contained sites and the strategic aspects of waste planning.

The work reported here complements that of the Environment Agency R&D project as this project is focused on data gathering and presenting the existing situation rather than developing guidance or presenting options for future policy. As such this project will provide a useful data source for the Environment Agency project in addition to the objectives already mentioned.

At the time of completing this report (February 2000) the Environment Agency guidance on landfills below the water table had not been completed.

5. Results of Search for UK Sites

5.1 Introduction

To obtain data on existing hydraulically contained landfills, a search was undertaken for sites in the UK which are hydraulically contained. Existing sources of information were first identified and searched for relevant information. Subsequently, landfill operators were contacted with a questionnaire to identify their hydraulically contained sites.

5.2 Data Sources

The main sources of data for the project were as follows:

- Environment Agency Database. A database was created in 1994 by WRc plc listing every landfill in England and Wales whether currently licensed or closed. The database is not publicly accessible and so is not referenced further;
- "The Sitefile Digest" (Landmark Information Group Ltd, 1999) lists key details of all the licensed waste management facilities in England, Scotland & Wales. The database was originally produced by Aspinwall & Co but subsequently the publication rights were purchased by Landmark and the database re-issued in 1999. Both the Aspinwall and Landmark versions of the database were consulted for this project;
- Landfill Operators;
- County Councils;
- The Environment Agency. The Environment Agency was contacted directly for access to the WRc database and at both regional and area level to find public access information on specific landfills;
- Scottish Environmental Protection Agency (SEPA);
- Environment & Heritage Service, Department of the Environment, Northern Ireland;
- Information held by Entec and Entec staff personal knowledge.

Many landfill operators contacted expressed enthusiasm and interest in the project but several requested that their sites were not identified. For this reason Entec have not named any of the sites discussed in this report.

5.3 Initial Data Gathering Exercise

5.3.1 Environment Agency Listings

An objective of the project was the creation of a master listing of all the sub water table landfills known to the Environment Agency. This was initially pursued by a combined approach to the Environment Agency and regional waste managers for information about landfills within their regions, and consultation of the WRc landfill database. The first approach was halted before completion following an internal Environment Agency meeting in early February 1999. At this meeting the regional waste managers decided that Entec's query should be dealt with at a national level using the WRc database.

Table 5.1 below summarises the replies received from the Environment Agency Regional Offices, SEPA and EHS (for Northern Ireland).

Table 5.1 Responses to Initial Environment Agency/SEPA Survey of Sub-Water table Landfills

Region	Area	Operational	Closed	Proposed
North East	Ridings (except East)	8 landfills: 4 inert (of which 1 dewatered); 4 non-inert (of which 3 dewatered)	2 landfills, both inert and not pumped	None
North East	Northumbria	1 landfill: non-inert, dewatered	None	None
South West		2 landfills: non-inert (not dewatered)	2 landfills: both non-inert and pumped	3 landfills: non-inert and dewatered
SEPA North	West	None	None	None
SEPA North	East	None	None	None
SEPA East		1 landfill, non-inert		

Note: Consultation with the Environment Agency was halted before completion, replies were not received from all regions only those regions which replied are listed above.

A listing from the WRc database was obtained in April 1999. The listing includes, in principle, all landfill sites in England and Wales which have the base of the waste below the water table at any point at present (or in some cases in the future). However, the database was constructed in 1993/94 and to the best of our knowledge has not been updated since. The numbers of non-inert, hydraulically contained landfills identified by this query were 199 (open) and 296 (closed). Inert landfills were also listed, with 154 open and 245 closed.

An attempt was then made to establish the identity of the site operator for each landfill (for reasons of confidentiality this information was not released by the Environment Agency). The listing of operational non-inert sites listing had 199 entries, there were however, a number of duplicate entries and the list was reduced to 175 sites after adjustment for these.

The adjusted list was checked against "The Sitefile Digest" (a public access listing of Waste Management Licences). Operators of only 103 (59%) of the 175 sites were identified from

Sitefile. A total of 79 operators were identified for the 103 sites, although the number of operators has been reduced to 73 since the time of publication by mergers and acquisitions. It is clear that the majority of landfill operators had just a single hydraulically contained site. Landfill operators identified as having more than one site were: Cory Environmental Ltd, Hanson Waste, JC Waste, Waste Recycling Group (Lincs Waste), NEWS, RMC Environmental, Shanks, SITA, Summerleaze, Viridor and Wastewise.

5.3.2 Questionnaire Q1

The 73 landfill operators of the 103 potentially hydraulically contained landfills identified from the process described in Section 5.3.1 were contacted with a questionnaire designated as Q1. A copy of the Q1 questionnaire is included in Appendix A. The primary objective of the questionnaire was to divide landfills into three categories:

i) Definitely not sub water table;

ii) sub water table without hydraulic containment;

iii) sub water table with hydraulic containment.

Of the 73 operators contacted, a total of 17 replied with completed questionnaires. From this a further three hydraulically contained sites were identified.

As the landfill operators of all 175 sites listed on the WRc database could not be identified by the process described in Section 5.3.1, Q1 questionnaires were sent to 20 additional major landfill operators and to 37 county councils. In total 130 (73+20+17) organisations were sent the questionnaire, of which 39 organisations responded, but with completed questionnaires for only 30 sites and incomplete questionnaires for a further 13 sites. From the information contained in the completed Q1 questionnaires, at least 16 (~50%) of the operational sites identified from the WRc database as being hydraulically contained are not in fact even sub water table.

It became clear over the course of the initial data collection exercise that there were a number of practical difficulties in obtaining relevant information. In particular the concept of sub water-table and hydraulically contained landfill was not well understood by many landfill operators, and hence they could not appreciate the potential benefits of their co-operation with the data collection exercise. As a result many did not complete and return the questionnaire.

In addition, it was not always clear who the appropriate member of staff was to answer the questionnaire and there was often doubt as to whether the information was available for release to third-parties.

As the concept of hydraulic containment is not always fully understood, suitable monitoring data for assessing performance is not always gathered to determine the status of a site.

Information on closed sites (of which the original search identified 296) proved even more elusive. Only a small number of the county councils responded to the questionnaire, mostly to say that they did not consider that they had any sub-water table landfills.

A second questionnaire (Q2) was later used to gain further information about relevant sites (see Section 5.5). An example of the Q2 questionnaire is included as Appendix B.

5.3.3 Other Sources of Information

In addition to the Q2 questionnaire (see Section 5.5), Entec used a number of other approaches to gather information about hydraulically contained landfills. In particular, the public register maintained by the Environment Agency was consulted and in some cases copies of the Regulation 15 Groundwater Risk Assessment submissions were reviewed. Less formal approaches to Entec's own staff and their contacts were also carried out.

The supplementary approaches identified another 22 sites that are almost certainly sub-water table that were not given in the original listing from the WRc database.

Three of these landfills use the groundwater pumping strategy, discussed in Section 2.2.4. Entec is aware of one other proposal along these lines.

5.3.4 Conclusions of Initial Data Collection

The list of hydraulically contained landfills identified in the initial data collection exercise is presented in Table 5.2. For reasons of commercial confidentiality neither landfill names nor landfill operators are disclosed. The table categorises each of the 103 sites originally identified on the WRc database and with known operators, plus the additional 22 sites from other sources, under one of the categories listed below:

- Hydraulically contained and further information obtained (18 sites);
- Probably hydraulically contained (9 sites);
- Probably sub water table, but not hydraulically contained (17 sites);
- Water table lowering (pumping groundwater to avoid being sub-water table (3 sites);
- Not sub-water table (16 sites);
- No further useful information obtained (62 sites).

Thus the original listing of 103 potentially hydraulic contained landfills with known operators and the other 22 identified from other sources was reduced to only 27 probably or definitely hydraulically contained landfills. These 27 sites are discussed in more detail in Section 5.5.

Table 5.2 List of All Sub-Water Table Sites Identified in Environment Agency Database

	Environment Agency Region	County	Status*	First Questionnaire	Second Questionnaire
HYDRAULICALLY CONTAINED SITES					
1	Anglian	Cambridgeshire	H-C		Entec (permission given)
2	Anglian	Bedfordshire	H-C		Entec (permission given)
3	Anglian	Bedfordshire	H-C		Entec (permission given)
4	Welsh	Cheshire	H-C		Entec (permission given)
5	Anglian	Buckinghamshire	H-C		Entec (permission given)
6	Anglian	Northamptonshire	H-C		Pub Reg
7	Anglian	Northamptonshire	H-C		Pub Reg
8	Midlands	Leicester	H-C		Pub Reg
9	Thames	Berkshire UA	H-C	YES	Meeting
10	Thames	Hertfordshire	H-C	YES	Meeting
11	North East	Humberside	H-C	YES	Meeting
12	South West	Wiltshire	H-C	YES	Meeting
13	South West	Bristol	H-C	YES	Meeting
14	South West	Somerset	H-C	YES	Meeting
15	South West	Somerset	H-C	YES	Meeting
16	South West	Somerset	H-C	YES	Meeting
17	Midlands	Shropshire	H-C	No reply	Pub Reg
18	Thames	Bedfordshire	H-C	No reply	Entec (permission given)
PROBABLY HYDRAULICALLY CONTAINED SITES					
1	Anglian	Essex	Prob H-C	YES	No reply
2	Anglian	Essex	Prob H-C	YES	No reply
3	Anglian	Norfolk	Prob H-C	YES	
4	Southern	Sussex	Prob H-C	YES	No reply
5	South West	Devon	Prob H-C	YES	Meeting
6	Anglian	Essex	Prob H-C	YES	
7	Thames	London	Prob H-C	YES	
8	Anglian	Lincolnshire	Prob H-C	YES	
9	North West	Greater Manchester	Prob H-C	YES	
PROBABLY SUB WATER TABLE BUT NOT HYDRAULICALLY CONTAINED					
1	North East	Humberside	Poss sWT	YES	No reply
2	Thames	Berkshire UA	sWT	YES	
3	South West	Devon	Poss sWT	YES	
4	Anglian	Lincolnshire	Poss sWT	YES	
5	Thames	Berkshire UA	Poss sWT	YES - incomplete	
6	Thames	Oxfordshire	Poss sWT	YES - incomplete	
7	Thames	Oxfordshire	Poss sWT	YES - incomplete	
8	Thames	Oxfordshire	Poss sWT	YES - incomplete	
9	Anglian	Northamptonshire	Poss sWT	No reply	Pub Reg - no reply
10	Welsh	Denbighshire	Poss sWT	No reply	Pub Reg - no Reg 15
11	Welsh	Wales	Poss sWT	No reply	Pub Reg - no Reg 15
12	Anglian	Lincolnshire	Poss sWT	No reply	Pub Reg - no Reg 15
13	Anglian	Essex	sWT	YES	
14	Anglian	Essex	sWT	YES	
15	North East	Humberside	sWT	YES - incomplete	No data available
16	North East	Humberside	sWT	YES - incomplete	No data available
17	Welsh	Gwynedd	sWT	No	
GROUNDWATER PUMPING TO CREATE UNSATURATED ZONE					
1	Northeast	Yorkshire	GWP		
2	North East	North Yorks	GWP	YES	
3	Welsh	Wrexham	GWP	YES	

Table 5.2 (continued) List of All Sub-Water Table Sites Identified in Environment Agency Database

	Environment Agency Region	County	Status*	First Questionnaire	Second Questionnaire
NOT SUBWATER TABLE					
1	Anglian	Essex	Not sWT	YES	
2	Anglian	Norfolk	Not sWT	YES	
3	Thames	Hertfordshire	Not sWT	YES	
4	North East	North Yorks	Not sWT	YES	
5	Thames	Berkshire UA	Not sWT	YES	
6	Anglian	Norfolk	Not sWT	Yes - incomplete	
7	Midlands	Hereford and Worcester	Not sWT	Yes - incomplete	
8	Southern	Isle of Wight	Not sWT	Yes - incomplete	
9	North West	Greater Manchester	Not sWT	Yes - incomplete	
10	North West	Cheshire	Not sWT	Yes - incomplete	
11	North East	Durham	Not sWT	Yes - incomplete	
12	Anglian	Northamptonshire	Not sWT		Pub Reg
13	Thames	Buckinghamshire	Not sWT		Entec (permission given)
14	Anglian	Norfolk	Not sWT	No reply	
15	Anglian	Norfolk	Not sWT	No reply	
16	Anglian	Norfolk	Not sWT	No reply	
UNKNOWN - No response from operator					
1	Anglian	Northamptonshire		No reply	
2	North West	Greater Manchester		No reply	
3	Welsh	Torfaen UA		No reply	
4	Anglian	Norfolk		No reply	
5	Thames	Berkshire UA		No reply(2)	
6	North East	North Yorks		No reply	
7	North East	Cleveland		No reply	
8	Southern	Hampshire		YES - incomplete	Meeting - limited info
9	South West	Dorset		No reply	
10	Anglian	Cambridgeshire		No reply	
11	Anglian	Essex		No reply	
12	Anglian	Essex		No reply	
13	Anglian	Lincolnshire		No reply	
14	Anglian	Lincolnshire		No reply	
15	Anglian	Suffolk		No reply	
16	Welsh	Bridgend		No reply	
17	Thames	Berkshire UA		No reply(2)	
18	Midlands	West Midlands		No reply(2)	
19	Welsh	Newport		No reply(2)	
20	Thames	Buckinghamshire		No reply(2)	
21	Anglian	Essex		No reply(2)	
22	Thames	Berkshire UA		No reply(2)	
23	Midlands	Nottinghamshire		No reply(2)	
24	Anglian	Suffolk		No reply(2)	
25	Midlands	Nottinghamshire		No reply(2)	
26	Thames	Buckinghamshire		No reply(2)	
27	Welsh	Cardiff		No reply(2)	
28	Thames	Berkshire UA		No reply(2)	
29	Thames	Oxfordshire		No reply(2)	
30	North East	North Yorks		No reply(2)	
31	Welsh	Bridgend		No reply(2)	
32	Welsh	Vale of Glamorgan		No reply(2)	
33	Anglian	Essex		No reply(2)	

Table 5.2 (continued) List of All Sub-Water Table Sites Identified in Environment Agency Database

	Environment Agency Region	County	Status*	First Questionnaire	Second Questionnaire
34	Anglian	Essex		No reply(2)	
35	Thames	Buckinghamshire		No reply(2)	
36	Midlands	Shropshire		No reply(2)	
37	North East	Humberside		No reply(2)	
38	Thames	Oxfordshire		No reply(2)	
39	Thames	Oxfordshire		No reply(2)	
40	South West	Devon		No reply(2)	
41	North East	Humberside		No reply(2)	
42	North East	South Yorkshire		No reply(2)	
43	South West	Somerset		No reply(2)	
44	Anglian	Cambridgeshire		No reply(2)	
45	Anglian	Northamptonshire		No reply(2)	
46	Thames	Oxfordshire		No reply(2)	
47	Welsh	Newport		No reply(2)	
48	Thames	Oxfordshire		No reply(2)	
49	Welsh	Pembrokshire		No reply(2)	
50	Midlands	Nottinghamshire		No reply(2)	
51	Midlands	Leicestershire		No reply(2)	
52	North East	Humberside		No reply(2)	
53	North East	Durham		No reply(2)	
54	South West	Devon		No reply(2)	
55	Anglian	Suffolk		No reply(2)	
56	Anglian	Suffolk		No reply(2)	
57	Thames	Berkshire UA		No reply(2)	
58	Thames	Buckinghamshire		No reply(2)	
59	Anglian	Lincolnshire		No reply(2)	
60	Anglian	Suffolk		No reply(2)	
61	Welsh	Flintshire		No reply(2)	
62	Anglian	Essex		No reply(2)	

Note: H-C = hydraulically contained, sWT = sub-water table, GWP = groundwater pumping

5.4 Total Number of Hydraulically Contained Landfills

5.4.1 Sub-Water Table Landfills

Based on the information gathered as part of this project, conclusions have been drawn on whether a particular site is sub-water table or not for 63 operating landfills out of a total of 125 possible (WRc database and other sources, see Table 5.2). 16 of the 63 sites are not sub-water table and 22 were identified from sources other than the WRc database. This means that only 33 out of the 103 WRc database identified sites were sub water table and so the WRc database appears to have an accuracy of approximately 30% (from the limited data obtained).

Assuming that a ~30% accuracy extends to the remaining 72 (175-103) sites identified on the WRc database, it is tentatively deduced that there could be a further ~20 sites in addition to the 47 (63-16) known sites. So a total of about 70 sub water table sites in England and Wales. In Scotland only one potentially sub water table site has been identified and few others are anticipated to exist there.

The information gathered on closed landfill sites was very limited. The County Councils that replied to Entec's questionnaires typically indicated that they did not have any sub water table landfills. Given that the search of the WRc database indicated nearly 300 closed, sub-water-table landfills, there is likely to be a significant number. A few of these closed sites may be sub water table, but Entec has only succeeded in identifying a single site.

Older, closed, sub-water table sites, particularly dilute-and-disperse (or unlined) sites, are not likely to control leachate in a way which makes them hydraulically contained. Only sites closed in recent years, probably since the introduction of the Waste Management Licensing Regulations in 1994, are likely to have appropriate leachate control mechanisms in place.

5.4.2 Hydraulically Contained Landfills

Entec is reasonably confident that of the 47 (63-16) probable or definite sub water table sites, at least 27 (18+9 in Table 5.2) of the sites are intentionally keeping leachate levels lower than the surrounding groundwater table. This is about 50% of the known sub-water table sites and so it is possible that there may be about 30 to 40 (~70 x ~50%) active hydraulically contained sites in England and Wales. One closed landfill has also been identified which is hydraulically contained. The only sub-water table site in Scotland does not appear to be hydraulically contained.

Of 61 landfills whose operators did not respond to questionnaire Q1, only a small number are owned by companies with more than one site on the list. It is clear from the overall response to both of the questionnaires that the 'smaller' operators (i.e. those owning only a single site) were less likely to respond to the questionnaire than multiple site operators.

Though some of these small-operator sites may well be sub-water table, only a few are likely to operate a policy of hydraulic containment because of the level of technical experience and understanding required to propose and obtain regulatory approval for such schemes, or indeed to operate them. There will be exceptions, but it is unlikely that more than 2 or 3 out of the 61 landfills are hydraulically contained. This means that the total number of hydraulically contained sites may be closer to 30 than 40.

There remains the possibility that other sites exist which are not on the WRc database and which Entec did not identify. Since at least two of the major landfill operators declined to co-operate with the project, it is not implausible that a further 5 to 10 hydraulically contained sites have not been identified.

In summary the total number of hydraulically contained sites in England and Wales is probably between 30 and 40. In Scotland and Northern Ireland, there is no evidence that any sites operate in this way.

5.5 Detailed Information Gathering

5.5.1 Introduction

Following the compilation of estimates of the total number of hydraulically contained sites in the UK, more details were sought on the approach taken to hydraulic containment at specific landfills and its effectiveness in preventing groundwater contamination. The data were obtained by means of a second questionnaire (Q2) which was typically completed during an interview with the landfill operator although some of the forms were completed by the operator. For sites where Entec has been involved as a consultant, Entec staff completed the questionnaire with the permission of the operator. Information for some sites was obtained from Environment Agency Waste Management Public Registers.

For many of the sites, a confidentiality condition was imposed on the use of the data. For this reason individual sites have not been identified by name or operator.

5.5.2 Results

Table 5.3 summarises the 18 hydraulically contained sites for which details have been obtained. For each of these 18 sites a short description of the site is included in this Section. Table 5.4 gives brief details of the 9 sites which are "probably" hydraulically contained but for which no detailed information was obtained. A more detailed description of each site listed in Table 5.3 is given in Appendix C.

Table 5.3 Summary of Detailed Case Study Analysis (all hydraulically contained)

Site Ref	Location	Liner	Hydraulic ally Contained	Base of waste relative to WT	Leachate level relative to WT	Pumping Rate (m3/y)	Hydrogeology below base	Aquifer
A	Wiltshire	No	Y	-32 (artesian)	-22 (artesian)	60,000	Kimmeridge Clay over Corralian Limestone with a thin artesian sand layer in the clay	Non
B	Yorkshire	1m Reworked MM	Y	-4 & -10	-2 & -8		Mercia Mudstone	Minor
C	Wiltshire	No	Y	Down to -9	-7 to -9	20,000	Mercia Mudstone over Carbonaceous coal	Minor
D	Hertfordshire	1 m engd clay	Y	-2.5	-1.5	4,400	Sand & Gravel over London Clay	Major
E	Berkshire	1 m engd clay	Y	-30	-9	11,000	Sand & Gravel over Tertiary Clay	Major
F	Somerset	No	Y	-4	-1 nominally (but not currently achieved)	25,000	Lias Clay	Minor
G	Somerset	Clay + HDPE	Winter only	Seasonal +0.5 to -2.5	Seasonal +2/5 to -0.5	35,000	Alluvial silts & clays over Lias Clay/Limestone	Minor
H	Somerset	Clay	Y	-15.5	-7.5	80,000	Mercia Mudstone with perm layer 5 m below waste	Non
I	Northampton	Clay	Y	No data	-17 to -27	No data	Lias clay over Limestone/marl	Minor
J	Northampton	Clay	Partly	No data	+3 & -6	No data	Lias clay over limestone/marl	Minor
K	Leicester	No	Y	-31 to -52	-25 to -49	200,000	Granodiortite intrusion in Mercia Mudstone	Non

Table 5.3 (continued) Summary of Detailed Case Study Analysis (all hydraulically contained)

Site Ref	Location	Liner	Hydraulically Contained	Base of waste relative to WT	Leachate level relative to WT	Pumping Rate (m3/y)	Hydrogeology below base	Aquifer
L	Bucks	In situ clay	Proposed	0 to -36	+8 to -6 now, 0 to -10 proposed	"Minor"	Oxford Clay over Kellaways Sand over Great Oolite Limestone	Minor
M	Bedfordshire	Partly 1 m engd clay	Proposed	-25 to -50	+3 to -6 now, -6 to -11 proposed		Oxford Clay over Kellaways Sand over Great Oolite Limestone	Non
N	Cheshire	1 m engd clay	Y	-12	-10.5	Up to 18,000	Ruabon Marl over Middle Coal	Minor
O	Cambs	No (but in Oxford clay)	Partly (also GW pumping)		-9 (but some perching)		Minimum 1 m Oxford Clay over Kellaways Sand over Great Oolite Limestone	Non
P	Hertfordshire	Partly 1 m engd clay	Y		-10 to +2 but proposed -5		Gault Clay over Woburn Sands	Minor
Q	Bedfordshire	Partly 1 m engd clay	Partly		+11 and -7		Oxford Clay over Kellaways Sand over Great Oolite Limestone	Non
R	Shropshire	1 m engd clay	Partly	-6	-4		Upper Coal Measures	Minor

Note: The data in these tables is often a representative value of a parameter that varies in time and across the area of the landfill. The values should be taken as indicative only.

Table 5.4 Other Probable Hydraulically Contained Sites

Refer	Location	Liner	Hydraulically Contained	Base of waste relative to WT	Leachate level relative to WT	Pumping Rate (m3/y)	Hydrogeology below base	Aquifer
S	Essex	Eng clay	Probably	No data	-8 to +1	24,000	London Clay	Minor
T	Norfolk	HDPE+BES	Relative to S&G	-15	-12 to -15	3,700	S&G over clay over chalk	Major
U	Sussex	1m Eng Clay	Y	GW artesian	GW artesian	Not at present	Gault clay over Lower Greensand	Non
V	London	1m Eng Clay	Y	No data	+1 to -10	Not at present	Gravel over London Clay	Minor
W	Manchester	HDPE	Probably	No data	+6 to -5	40,000	Clay Drift over Middle coal	Minor
X	Essex	clay	Probably	No data	0	No data	Clay over S&G over London Clay	Non
Y	Essex	0.75m Eng Clay	Y	-8 to -19	-2 to -18	No data	S&G over London Clay	Minor
Z	Devon	2m clay and HDPE	Will be	-3	-1	3,900	Permo-Triassic Sandstone	Major
A1	Lincs	Clay lined	Probably	No data	No data	No data	Sands & Gravels	Minor

Note: The data in these tables often include a representative value of a parameter that varies in time and across the area of the landfill. The values should therefore be taken as indicative only.

5.6 Discussion of Survey Results

5.6.1 Geographic Distribution

A total of 27 landfills that appear to operate a hydraulic containment system have been identified through the search process. The numbers in each Environment Agency Region are given in Table 5.5.

Table 5.5 Geographical Distribution of Hydraulically Contained Landfills

Region	Number of Hydraulically Contained Sites	
	Definite Sites	**Probable Sites**
Northeast	1	
Northwest		1
Midlands	2	
Anglian	6	5
Southwest	5	1
Thames	3	1
Southern		1
Wales	1	
TOTAL	18	9

From the data in Table 5.5 it is apparent that the majority of the identified hydraulically contained landfills are located in Southern and Eastern England. The locations of a possible further 5 to 10 sites is not known.

5.6.2 Environment Setting

Using the groundwater vulnerability classifications of the Environment Agency, there are 8 hydraulically contained landfills on non-aquifers, 15 on minor aquifers and 4 on major aquifers. Table 5.6 summarises the geological strata within which the sites are situated.

Table 5.6 Geological Distribution of Hydraulically Contained Landfills

Main Geological Formation	Number of Hydraulically Contained Sites Definite Sites	 Probable Sites
Sand & Gravels		2
Sand & Gravel over Tertiary Clay	2	3
London Clay		1
Gault Clay over Woburn Sands	1	1
Clay over Corallian Limestone	1	
Oxford Clay over Kellaways Sand and Great Oolite Limestone	4	
Lias Clay (±over limestone/marl)	4	
Mercia Mudstone	4	
Sherwood (P-T) Sandstone		1
Ruabon Marl over Middle Coal Measures	1	
Clay Drift over Middle Coal Measures		1
Upper Coal Measures	1	
TOTAL	18	9

A significant number of the sites are situated on low permeability strata such as the Gault Clay, Oxford Clay, Lias Clay and Mercia Mudstone. The presence of many of these clays in Southern and Eastern England partly explains the geographic distribution of the sites.

In addition to the sites situated in clay-rich strata, there are a number of sites, which appear to be located within more permeable deposits, particularly sands and gravels. One site also appear to be situated within the Sherwood Sandstone.

5.6.3 Liner Design

The design of the liner at the hydraulic contained sites varies between no liner (but on in situ clays), one metre of engineered clay to composite liners of HDPE over clay or BES. The types of liner are summarised in Table 5.7.

The most common liner type is 1m of engineered clay or no liner, but on in situ clays. This liner design has been in common usage in all landfill sites for 5 to 10 years. The use of clay lining is also likely to be linked to the availability of clay for re-engineering in these largely clay-rich formations.

The highest standard liners (in terms of lowest permeability) in use are composite liners of HDPE over BES for a site in sand and gravels over clay over Chalk and HDPE over 2m engineered clay for a site in Permo-Triassic Sandstones. The higher level of physical containment design for these sites is likely to be a function of the receptor (aquifer) sensitivity. This higher level of design may be being used as a safety factor, but otherwise appears to be ignoring the hydraulic containment at these sites.

Table 5.7 Designs of Liner in Use at Hydraulically Contained Landfills

Liner Design	Number of Hydraulically Contained Sites	
	Definite Sites	Probable Sites
No liner (on Granodiorite in Mercia Mudstone)	1	
No liner (in situ Clay)	5	
~1 m Engineered Clay (some with older cells on in situ Clay)	11	6
HDPE on (in situ) Clay	1	2
HDPE over BES		1
TOTAL	18	9

It is noted that there are 5 sites situated on non-clay strata, mainly sands and gravels, for which the liner design comprises only engineered clay. It is not clear whether this relatively low level of design has been accepted due to a hydraulic containment argument.

5.6.4 Potentiometric Levels

The bases of all of the sites are situated at or below the local potentiometric level, but the depths below vary significantly between a few metres and 50 m. At one of the sites, the base of the waste is only below the local potentiometric level in winter and so is only seasonally hydraulically contained.

There is no obvious relationship between sites in clay-rich strata being further below the local potentiometric level than sites in more permeable strata such as sands and gravels. This suggests that some of the sites would have had significant dewatering prior to engineering of the liners and landfilling.

5.6.5 Leachate Levels

The relative elevations of leachate levels and potentiometric levels at the 27 likely hydraulic contained sites are summarised in Table 5.8.

One site is only seasonally hydraulically contained and seven sites include parts of their areas which are not hydraulically contained. Otherwise the level of hydraulic containment is typically less than 10 m, but four sites have leachate levels between 10 and 25 m below potentiometric levels and one site maintains a difference of between -25 and -49 m.

There is therefore a large degree of variability in the degree of hydraulic containment at each site. This is because the leachate level strategies used at the hydraulically contained landfills examined in detail are all based on a fixed maximum leachate head above the landfill base. In other words the leachate head, as measured in any and all monitoring boreholes and sumps, is not to exceed a certain fixed level above the base. This means that hydraulic containment is effectively being ignored or if not, the safety margin imposed is large.

Table 5.8 Relative elevations of Leachate Levels and Potentiometric Levels

Leachate Level Relative to Potentiometric Level* (m)	No of Hydraulically Contained Sites	
	Definite Sites	Probable Sites
Seasonally hydraulically contained (+0.5 to -2.5)	1	
Variably contained between +10 and -10	4	3
Contained between 0 and -10	10	2
Contained between -11 to -25	2	2
Contained between -25 and -50	1	
No data		2
TOTAL	18	9

Note: * The range in levels at some of the sites covers more than one range in the table, so the predominant range is used. Some sites also contain cells or areas where leachate levels are in excess of potentiometric levels.

Entec is aware of proposed more flexible operating rules for both operating and proposed sites, which would define that the maximum leachate must be a fixed depth below the groundwater level measured in piezometers outside the landfill.

From the survey results and Entec's experience it appears that flexible leachate level strategies based on external groundwater heads have only been accepted at one landfill site and proposed but not yet accepted at several other landfills.

5.6.6 Leachate Extraction

The quantities of leachate extracted at the identified sites varies between "minor" assumed to be less than a tanker a week so ~1 000 m^3/a (Site L) to 200 000 m^3/a (Site K). The amount of leachate extraction will depend on a number of variables including:

- the area of the site;
- the degree of capping of the site;
- the amount of liquid wastes imported;
- the age of the waste, the degree of saturation and the amount of recirculation occurring;
- the amount of groundwater ingress which in turn depends on;
  - the hydraulic conductivity and thickness of the liner and side walls;
  - the difference between leachate levels and potentiometric levels;
  - the basal area of the site;

If it is assumed that each site is managed in a similar way with capping of the waste soon after completion of each cell, that recirculation occurs until the waste is saturated, that each landfill has a similar liner hydraulic conductivity (i.e. 10^{-10} to 10^{-9} m/s), then the volume of leachate extracted per unit area of site (ha) should correlate with the difference between leachate and potentiometric levels. This assumption is tested in Figure 5.1.

Figure 5.1 suggests that despite there being a number of other variables important in controlling leachate extraction, there appears to be at least a limited correlation between the difference in leachate levels and potentiometric levels, i.e. the driving gradient for flow into the site. This is an important result.

The highest extraction rates (5 000 to ~36 000 m^3/ha/d) are in landfills constructed sub-water table within the Mercia Mudstone and where there is either no liner and side walls. Importantly, Site H has the highest extraction rate and thus inflow rate despite having a composite HDPE over engineered clay liner. The inflows are likely to be a result of the absence of side wall lining in half of the site. The large inflows in all of these Mercia Mudstone sites, are compatible with a hydraulic conductivity of between 10^{-9} and 10^{-8} m/s; which is a plausible range for this often silty clay formation.

Smaller, but still significant extraction rates (~1700 to ~1850 m^3/ha/d) are also seen at Sites A and E. Site A is unlined, but sits within the Kimmeridge Clay and contains low permeability Cement Kiln Dust (CKD) waste. Site E is lined with 1m of engineered clay, but sits within sands and gravels. The inflows into both of these sites is compatible with a hydraulic conductivity of between 10^{-10} and 10^{-9} m/s; and this is a plausible range for in situ and engineered Jurassic Clays.

So, groundwater ingress appears to be occurring at hydraulically contained sites, as would be expected, and that the rate of ingress appears to depend on the driving head into the site as well as the presence and hydraulic conductivities of basal and side wall liners and of the surrounding strata. Notably the highest inflow occurs at a site designed with one of the highest standards of basal liner (HDPE over clay); a composite liner designed to minimise leakage downwards and out through the base of the liner. The high leakage here is however due to the absence of side wall lining and containment through in-situ Mercia Mudstone.

5.6.7 Evidence of Contamination

Impacts on groundwater and surface water were not identified at any of the sites looked at in detail, with the exception of two leachate breakouts at surface which occurred at site Q.

An article in ENDS (1997) quoted an unpublished report commissioned by the NRA reviewing the impacts of landfills on groundwater. A list of the 15 sites posing the greatest "actual or potential" threat was presented (all with observed "major" impacts on groundwater quality). A further 9 sites were listed at which monitoring was not taking place but where concern was expressed that an impact may have occurred based on the site characteristics. None of these sites is hydraulically contained. All are dilute and disperse with unsaturated zones of less than 5 m thickness.

5.6.8 Loss of Water Resources

Any groundwater which enters a hydraulically contained landfill site will become leachate, and therefore will be lost as a water resource. An attempt is made here to estimate the total loss of water resources for all hydraulically contained landfill sites in the UK.

The total amount being pumped from the sites identified (Table 5.3 and Table 5.4) is more than 525 000 m^3/a (1.4 Ml/d). Where there is no entry in Table 5.3 or Table 5.4 in the relevant column it is not known whether the site is pumping very little leachate or whether it is pumping an unknown quantity.

There is no information on the volumes of leachate pumped for approximately 45% (12 of 27) of the sites studied in detail, but the average volume pumped per site with an entry is 33 000 m^3/a (0.09 Ml/d). Assuming that the average per site is applicable to the 40 or 50 sites believed to exist in the UK then the total leachate pumping requirements for all the sites in the UK is of the order of 1 320 000 m^3/a to 1 650 000 m^3/a (~3600 to 4500 m^3/d).

A proportion of the leachate pumped from each site will be due to infiltration of rainfall entering the top of landfills and this must be accounted for as this would result in leachate generation whether a site is hydraulically containment or not.

Infiltration to a capped site is typically assumed to be around 50 mm/a. The average area of the sites for which there are data is about 40 ha, and so annual cap infiltration would amount to some 20 000 m^3/a (~55 m^3/d) per site and an estimated 800 000 to 1 000 000 m^3/a (~2200 to 2700 m^3/day) in total for the UK. The volume of leachate generated by infiltration is estimated to be of the order of 50 to 75% of the total volume being pumped out from the landfills suggesting that, in general, groundwater inflows are significant, but not large.

Given the broad assumptions and the inherent dangers in subtracting two similar numbers with very wide potential ranges, it is not sensible to estimate what the impact on water resource is of using hydraulic containment instead of above-the-water-table containment. It is, however, possible to say that the loss of water resources is likely to be small, say less than 1000 to 2000 m^3/d for the whole UK.

To put this volume in context, the volume of water put into public supply in England and Wales in water year 1994/95 was 16 489 000 000 m^3/d and a single public water supply borehole can often produce 10 000 000 m^3/d . It is reasonable to conclude that the volume of water involved is negligible to national water resources. Locally, each landfill on average will be similar to a small abstraction of about 20 to 50 m^3/day.

5.6.9 Long-Term Performance

Data have not been collated for all sites on their age, but start dates are known for some. Landfilling has been active at some of the locations since the 1940's, but these older areas were dilute and disperse, above water table sites. For those sites where the period of operation is known, the oldest sites opened in the late 1970's, but have not until recently intentionally operated as hydraulically contained. These sites are largely within the low permeability Oxford Clay and leachate extraction which has taken place appears to be recirculated. Besides there being little evidence of contamination at these sites, there is little information on which to assess the long term performance of the site.

Site H has been in operation since 1981 and is currently active. Leachate is extracted at a rate of about 80 000 m^3/a and discharged to sewer. No evidence of groundwater or surface water contamination is reported at the site. Leachate quality data have not been collated as part of this study, to allow a check on the impact of this rate of flushing of contamination on leachate quality at the site.

5.7 Summary of Survey Findings

In summary the findings of the survey are:

- The identification of hydraulically contained sites has been difficult, in part due to operator's and County Council's lack of understanding of the issue or their sites, but also due to lack of co-operation from some Waste Contractors and local councils, and a nervousness in co-operation from the Environment Agency.
- Significant errors (accuracy has been estimated at 30%) have been identified in the Environment Agency's landfill database collated by WRc in 1994. The database is not publicly accessible and many of the errors may be due to incomplete or inaccurate information supplied to WRc when they undertook the survey. However, it is apparent that there is not an accurate record of the number of hydraulically contained sites in the UK and this Entrust report is likely to be the best estimate at this time.
- The survey suggests that there are at least 27 hydraulically contained sites within the UK and there are estimated to be as many as 40 to 50 in total.
- A significant number of the sites appear to be located in southern and eastern England, but there appears to be hydraulically contained sites within each Environment Agency Region of England and Wales.
- Many of the hydraulically contained sites are within lower permeability (non-aquifer) strata such as the Jurassic Clays and the Mercia Mudstone. This may, in part, explain the predominance of sites in southern and eastern England. There are however sites which are situated within sands and gravels and there is one in the Sherwood Sandstone. These formations are designated as Major Aquifers.
- The engineered containment system varies from no lining, 1 m of engineered clay as a basal liner and sometimes as a side-slope liner, to composite basal liners of HDPE over clay and HDPE over BES.
- Leachate levels vary in elevation above the base of each site and with respect to the potentiometric levels. Most of the sites operate on the basis of a fixed leachate level above the base of the site rather than below the local potentiometric level. This means that most of them appear to be assuming leachate leakage through the liner rather than minimising groundwater ingress through their operation. Leachate levels are typically no more than 10 m below the local potentiometric level, but four sites have leachate levels between 10 and 25 m below potentiometric levels and one site maintains a difference of between 25 and 49 m.
- The volumes of leachate extracted at a number of sites strongly indicates that groundwater ingress is occurring. The amount of ingress appears to be dependent on the difference between leachate levels and potentiometric levels, but also the hydraulic conductivity of the lining system or surrounding strata. The highest ingress equivalent to ~35 000 m^3/ha/a is however at a site with a HDPE over clay composite liner, but with no side wall lining in the Mercia Mudstone. This rate of ingress is considerably higher than could be expected for an uncapped site with say 3-400 mm/a effective rainfall (equivalent to 3-4 000 m^3/ha/a).

- The rate of groundwater ingress averaged across each of the sites appears to be of the order of 20 to 50 m^3/day and this is equivalent to only a small agricultural abstraction in terms of groundwater resources.
- Some of the sites have been in operation since the late 1970's, but there is no reported evidence of groundwater or surface water contamination around any of the sites.

6. Design of Hydraulically Contained Sites

6.1 Introduction

Based on the findings of the literature survey (Sections 3 and 4) and the site survey (Section 5) and consideration of the general issues raised for landfills in Section 2, this section aims to provide some initial guidance on the approach which should be taken to assessing the suitability of a hydraulically contained site.

6.2 Planning and Licensing

The available legislation and guidance (see Section 3) indicates that hydraulic containment may be permitted if the hydrogeological conditions are suitable and the engineering measures are acceptable. The suitability of the hydrogeological conditions includes seasonal and long term variations in water levels. The engineering aspects include risks of hydraulic heave and other failure scenarios for the liner which could lead to direct discharges of List I substances through the failed liner to groundwater, and the sustainability of any long term groundwater abstraction.

It could be concluded from the above that hydraulically contained sites would be accepted if it could be demonstrated that the liner or liners could be emplaced without significant risk of failure. Also, that long-term groundwater abstraction was not necessary and that the additional leachate abstraction was sustainable, and that leachate levels could be maintained safely below those in the surrounding strata for the lifetime of the site.

6.2.1 Hydrogeological Setting

In the UK, hydraulically contained sites are currently being operated in a range of hydrogeological settings in non-aquifers, minor aquifers and major aquifers. There is therefore no strict precedent on the hydrogeological setting.

6.2.2 Non Aquifer Sites

A large number of the sites occur within clay-rich formations such as the Jurassic clays of southern and eastern England and this is likely to reflect a combination of factors. Some of the sites are former clay-pits for brick manufacture and due to their location in non-aquifer strata are obvious choices for the landfilling of putrescible wastes. The fact that these sites are sub-water table and hydraulically contained may be, at least for some sites, a function of naturally very shallow potentiometric levels and historically set licence conditions to maintain leachate levels below the ground surface to prevent surface breakout.

Landfills within clay-rich strata have different characteristics to those where the waste extends beneath the water table in an aquifer. The clays are aquicludes (non aquifers) that confine and protect the aquifer beneath (although at some sites much of the clay has been removed and a local minor aquifer layer lies close to the base of the site). Whether a water table truly exists within an aquiclude is itself a topic for discussion. It is possible for the head in a confined layer to be above the base of the waste, but there is still an unsaturated zone beneath the landfill (see

Figure 6.1). However, even where a potential is measurable in a piezometer, the capillary fringe will be several metres thick and the clay will be largely saturated right up to its top surface for much of the year.

The risks to groundwater from these landfills are likely to be significantly less than from landfills situated **above** water tables in permeable strata because of the hydraulic barrier and the physical barrier formed by the clay and its large attenuation potential.

Whether such landfills need to use hydraulic containment at all in view of the extremely limited potential for contaminant movement is doubtful. The use of hydraulic containment does however, offer additional reassurance of the ability of the landfill to minimise impacts on groundwater.

Given the likely lower risks to useable groundwater from landfills within clay-rich strata, this should mean that the safety factors in the landfill design should be lower than in minor and major aquifer sites.

6.2.3 Minor and Major Aquifer Sites

The survey has identified two definitely and one probably hydraulically contained sites within major aquifer sands and gravels and one probably hydraulically contained site in Permo-Triassic Sandstones. There are a number of other sites on minor aquifers such as sands and gravels, the Mercia Mudstone, local limestone formations and the Coal Measures.

Some of these more permeable formations have less natural attenuation capacity than the clay-rich formations discussed in Section 6.3.1. This means that the safety factors in the design of landfills in these more permeable formations should be higher than those within the clay-rich formations.

6.3 Potentiometric Levels

Potentiometric levels in the adjacent strata control the degree to which a site can be hydraulically contained. At some of the survey sites, potentiometric levels are tens of metres above the base of the waste and leachate levels, whilst at other sites, the difference may be only a few metres. An important issue is therefore to assess the seasonal variation and potentially long term variation in potentiometric levels at hydraulically contained sites.

6.3.1 Seasonal Variations

At some of the sites surveyed, the seasonal variation in potentiometric levels of the surrounding formation means that the leachate in the waste is only seasonally hydraulically contained. Given that at times of low potentiometric levels, there is a potential for leachate movement out of the site, then those sites with little attenuation potential in the liner or in situ strata may pose a risk to groundwater.

For unlined sites, seasonally hydraulically contained are only likely to provide low risk to usable groundwater in clay-rich formations. Without supporting leachate quality data, it may also prove very difficult to convince regulators that direct discharge of List I substances will not be significant under these circumstances. The requirements of both the Groundwater Directive and the Landfill Directive may therefore not be met.

For lined sites, it will be necessary to assess the seasonal movement of contaminants outwards in the liner and groundwater ingress back through the liner (see also Section 6.9 on risk assessment). Where there is a net movement of contaminants out of the site it will be necessary to assess the potential discharge of List I substances and the pollution potential of List II substances.

It is noted that a seasonal decline in the water table below the base of the waste may have the advantage that oxygen would be drawn beneath the landfill in the summer as the water table fell, possibly encouraging aerobic degradation. For a wide range of organic compounds aerobic degradation is faster than anaerobic degradation.

6.3.2 Long Term Variations

At some sites, potentiometric levels may increase or decrease over a number of years and this may affect the degree of hydraulic containment at a site.

Recovery of potentiometric levels may occur following:

- deliberate cessation of sub-liner groundwater pumping;
- reduction in leachate extraction rates and levels. The drawdown around a landfill could result from leachate pumping from the landfill acting as a large abstraction and creating drawdown around the site*;
- rebound of potentiometric levels in clay-rich strata due to loading effects and reduction in groundwater ingress into a lined former clay-pit void. At Site P the heads adjacent to the site have risen in some places. The rise is attributed to the loading effect as filling with waste takes place;
- cessation of deep mining activities (particularly relevant in Coal Measures sites);

Note*: *For the surveyed sites, several of the landfill operators mentioned that the "water table" often showed drawdown of groundwater levels around the landfill presumably because of groundwater flow towards the landfill (e.g. sites L, M and Q). Where the sites are situated in low permeability material, this can be caused by the transient effect of the original dewatering during extraction. Recovery of the groundwater pressure in clays may take years or even decades.*

A fall in potentiometric levels may occur following:

- re-established pumping from a previously dormant, but licensed abstraction well;
- dewatering associated with the extraction of minerals from adjacent areas.

Site assessments will need to examine the likelihood of any long term changes in potentiometric levels and the safety margins or engineered safety factors against the site losing its ability to be hydraulically contained.

6.4 Groundwater Control

Operational Phase

In clay sites, evaporation in summer may be sufficient to keep the open site dry and in winter groundwater inflows are likely to be a small component of total rainfall and surface runoff inputs. However, in more permeable formations, sub water table sites pump groundwater from boreholes or sumps during the operational phases of the landfill in order to keep the excavation dry. Once sufficient waste has been placed to overcome any potential hydrostatic heave and the site is suitably engineered, the groundwater can be allowed to rise and eventually the groundwater pumping can be stopped.

Long Term

At other sites the groundwater pumping is a policy carried out to artificially maintain an unsaturated zone. Three sites where this is the case were identified in Table 5.2 and Entec is aware of another large site where this is being considered.

Although this situation results in a landfill that is not sub-water table, it is mentioned as an alternative approach to a site that would be sub-water table.

6.5 Liner Design

6.5.1 General

There have been significant advances in the design of landfill liners for above water table sites. The main focus of these designs has been in the reduction of leakage through the base and into the underlying unsaturated zones. A brief discussion of liner types is included in Section 2.3.2.

For hydraulically contained sites, basal and side-slope liners are needed and there are four aspects to be considered for their design:

- reducing leakage into the site;
- ensuring the likelihood of liner failure is minimal;
- providing a protection layer during the operational stage against any short term (predicted or accidental) reversals in hydraulic gradient;
- providing an attenuation layer of sufficient capacity to prevent any impact to groundwater after site closure and eventual cessation of leachate extraction.

These points are discussed in greater detail in the sections below.

6.5.2 Reduced Leakage into the Site

At the surveyed sites, there is evidence of significant groundwater ingress from sites that are unlined. Some of these sites have highly engineered basal liners, but no side-slope liners.

Basal and complete side-slope lining is needed to help control the potential groundwater ingress into the site. The exact design of the lining system needs to take into account of:

- the capacity of the leachate extraction system to maintain leachate levels safely below the adjacent potentiometric levels;
- the capacity of the leachate treatment or disposal system;
- the need to accelerate waste stabilisation (see Section 6.9) with higher groundwater ingress flushing rates;
- the possible impact on local water resources (likely impact will be small for most sites);
- following closure of the site, the ability of the liner to minimise the discharge rate to groundwater of any unattenuated residual contamination.

Consideration of these points means that a high level of containment design would be chosen where the preference is to minimise leachate generation, and impact on water resources, but to pump smaller quantities of leachate for a longer period. Conversely, a lower hydraulic conductivity design may be more appropriate where high levels of leachate generation could be dealt with, and accelerated waste stabilisation and a shorter period of leachate extraction was preferred.

It is important to note that the composite action of HDPE over clay or BES only works where the HDPE is on the upgradient side of the leakage, so for hydraulic contained sites, that would mean adjacent to the strata rather than adjacent to the drainage blanket and waste. However, one option may be to use the standard arrangement and allow higher groundwater ingress during operation and eventual lower leachate leakage rates on completion.

6.5.3 Ensuring Likelihood of Liner Failure is Minimal

This will need an assessment of the liner failure mechanisms discussed in Section 2.3.3.

It is noted that should liner failure occur during the life of the site, then as long as the leachate control measures are adequate, then the hydraulically contained landfill still prevents leachate reaching the groundwater (in contrast to the above water table landfill which may not).

6.5.4 Providing a Protection Layer during Operation

The liner needs to provide a protection layer during the life of the site against:

- net diffusional movement of contaminants out through the liner against opposing groundwater ingress, providing attenuation capacity for ammonia and possibly organic contaminants;
- short term reversals in hydraulic gradient related to failure of leachate extraction systems or seasonal variations in potentiometric levels.

Such a protection layer is a requirement of the Landfill Directive for all sites.

6.5.5 Providing a Protection Layer after Site Closure

For each hydraulically contained site there will be a need in the future to cease leachate extraction and allow leachate levels to equilibrate with adjacent potentiometric levels. At this point there will be a potential for residual contaminants to move out of the site through the newly established local flow pattern.

To prevent contamination of groundwater by residual contamination, the lining system will need to:

- minimise impact from residual conservative, unretarded contaminants, by minimising leakage rates;
- minimise impact from residual ammonia and organics, by also providing adequate attenuation capacity.

It follows that a highly designed protection layer, in terms of low hydraulic conductivity and attenuation capacity, should in theory allow the earlier cessation of leachate extraction with a poorer quality of residual leachate. However, a lower hydraulic conductivity liner could also reduce the rate of groundwater ingress and flushing and so extend the period of waste stabilisation.

6.6 Leachate Control Measures

6.6.1 Requirements

The leachate control measures must be able to maintain leachate levels at a safe level below the potentiometric level in the adjacent strata. The level of safety will depend on:

- the variation in potentiometric levels;
- the ability of the collection system to reduce leachate levels over short periods (months);
- the redundancy in the leachate collection system;
- the ability of the liner to accommodate short periods of non hydraulic containment.

6.6.2 Options

Leachate control measures include the use of drainage layers or pipes above the basal and side slope liner and leachate extraction points. Drainage layers against the side slope lining helps to ensure that leachate cannot locally build up against the liner at perched levels. Monitoring points in these drainage layers also allow the required leachate level to be validated as lower than the potentiometric level in adjacent strata.

In physically contained sites, leachate extraction commonly involves pumping from a large sump on the cell base or from retro-fit wells. Pumping from a large sump on the cell base tends to be a more efficient method of collecting leachate, but there are issues about the longevity of such a system. Retro-fit wells can be re-drilled and so whilst less efficient, can be maintained for the life of the site.

For hydraulically contained sites, both basal sumps and retro-fit wells could be used. However, well-placed retro-fit wells may have the benefit of drawing water through the waste. Basal sumps connected to basal drainage and side slope drainage systems have the potential to collect a significant proportion of the groundwater moving into the site which has no benefit to waste stabilisation.

6.6.3 Leachate Level Strategies

The leachate level strategies used at the hydraulically contained landfills examined in detail are all based on a fixed maximum leachate head above the landfill base. In other words the leachate head, as measured in any and all monitoring boreholes and sumps, is not to exceed a certain fixed level above the base.

Entec is aware of proposed more flexible operating rules for operating and proposed sites, which would define that the maximum leachate must be a fixed depth below the groundwater level measured in piezometers outside the landfill.

A flexible approach is likely to be appropriate for landfills where the potentiometric level has a large range of fluctuation or in landfills in low permeability material. In the latter case, after dewatering during the construction and operational phases of development, the potentiometric level may take many years to recover to its natural rest level. For example, at Landfill L, the residual drawdown around the landfill is about 20 m. Were a fixed leachate level specified below the current groundwater level, then when the groundwater levels eventually recover, the pressure differential across the liner and side-slopes could be large. The disadvantages of having an unnecessarily large level difference between groundwater and leachate are that:

- more groundwater will enter the waste leading to more leachate generation;
- the risks of hydrostatic heave will increase (although the risks should be low where the landfill has been filled with waste).

In such a situation, a more pragmatic approach would be to increase the leachate levels as groundwater recovery occurs, whilst maintaining a sensible pressure differential.

Where the difference between leachate levels and potentiometric levels is kept small (1 or 2 m), careful control of leachate levels is necessary to prevent a reversal of the gradient between groundwater and leachate. For instance, a dry summer (falling groundwater levels) or a failure of a pump or trigger system (rising leachate levels) could result in leachate moving out of the landfill (the amount of movement depending on the liner specification and the head difference). However, given the extended contaminant transit times (years) through landfill liners, small periods of time (weeks to months) when a site is not hydraulically contained could probably be effectively reversed by over-compensating to pull contaminated water back into the landfill.

Some of the landfills examined have a more robust 5 to 10 m safety margin and three of the landfills (sites A, I and K) have a very robust containment policy, maintaining leachate levels of at least 22 m, 17 m and 25 m respectively below the water table. (It is not clear whether this differential is intentional or a result of maintaining a minimum 1-2 m leachate level above the liner). To permit such a head difference requires deep excavations which are also potentially a long way below the water table. Entec is aware of another landfill of this type at proposal stage in Northwest region. A large head difference gives an operator months to respond should a pump or a sump fail.

In cases where the management philosophy is to keep leachate levels a fixed amount below external potentiometric levels, it is necessary to decide which external potentiometric levels heads should be used for reference. The choice is between the original undisturbed potentiometric levels and the observed potentiometric levels at the landfill perimeter. In practice, it is important to demonstrate an inward flux and so potentiometric levels at some distance from the perimeter should be examined, although it is appreciated that this may prove difficult in terms of land access.

6.6.4 Perched Leachate

Perched leachate in the waste was noted as a problem in several of the landfills. Where leachate is genuinely perched and is not adjacent to the edge of the landfill, then it does not need to be considered for the purposes of hydraulic containment. The leachate head immediately adjacent to the liner will govern leachate leakage. However it is not always obvious that a high recorded leachate level is due to perched leachate or not. In this situation the Agency often adopts a conservative position and assumes that the true leachate level is being monitored.

6.7 Long-Term Pumping and Sustainability

6.7.1 Pumping Requirements

One of the Environment Agency's major concerns about hydraulically contained landfills appears to be is that they require active, rather than passive, long-term maintenance because of the pumping requirement. The approach proposed by operators is that pumping schedules are maintained until the waste has stabilised (as determined by the monitored leachate strength) and, as for above water table sites, continuation of pumping in the event that operators go bankrupt is effectively covered by financial provision.

It is important to note that the vast majority of above the water table physically contained landfills also have maximum leachate levels imposed as part of the licence conditions. These conditions are intended to keep the driving pressure gradient on the liner to a minimum. Operators must therefore maintain a leachate pumping system until the same 'stabilised' waste situation is reached as for hydraulically contained landfills. In this sense, management of hydraulically contained landfills is no more 'active' than that of above water table landfills.

6.7.2 Amount of Pumping

Above the water table landfills need to pump leachate to maintain leachate at a minimum level above the liner and so minimise liner leakage. For a capped site, the volume of leachate to be extracted is the difference between the cap infiltration and the liner leakage. For sites with a clay cap and engineered clay liner, the amount of leakage through the liner could plausibly be equal to the cap infiltration, so little leachate extraction would be needed. For the most highly engineered liners in above water table sites, the amount of leachate extraction needed could approach the cap infiltration (10 to 50 mm/a) so in the order of 100 to 500 m^3/a/ha.

For hydraulically contained sites, the volume of leachate to be extracted will be equal to the cap infiltration of about 100 to 500 m^3/a/ha, plus the groundwater ingress into the site. The amount of ingress into the site can be estimated by using Darcy's law for clay liners and the Giroud equations for geomembrane leakage (Giroud & Bonaparte, 1989), but only where the membrane is separated from the waste by a further low permeability layer (see Section 6.6.2).

For example, the rate of groundwater ingress through a clay liner 1m thick with hydraulic conductivity of 1×10^{-9} m/s and a driving leachate head of 2m is 620 m^3/a/ha (0.02 l/s). This would be the rate through base of the site, but it would also be necessary to consider the ingress through the side slopes. The highest total volume of leachate being extracted from the surveyed sites is about 35 000 m^3/a/ha. This is from a site with no side slope liners.

6.7.3 Duration of Pumping

In principle, pumping of leachate has to continue until the waste is fully degraded (as determined by the leachate quality monitoring, see Section 2.3.7 on Waste Stabilisation). The volume of water being pumped from the waste would be more for hydraulic containment as shown above.

To ensure the duration of pumping is minimised, the leachate control systems need to promote movement through the waste of the water entering the landfill, rather than, in the worst case, it flowing along the drainage layer before removal.

6.7.4 Sustainability

Hydraulically contained sites designed to draw the inflowing groundwater through the waste to leachate collection points have a greater potential of reaching waste stabilisation before capped above water table sites.

If it is assumed that a fixed volume of water needs to flow through the waste to achieve waste stabilisation, then a well designed hydraulic containment site should pump a similar volume of leachate over its shorter life than an above water table landfill site. The main difference will be that the above water table landfill site will not have to pump the quantity of leachate that leaks through the liner.

Thus in terms of sustainable development, the energy consumed by pumping and disposal of the extra leachate at the hydraulically contained site is unlikely to be significant. This extra energy consumption in the shorter term needs to be assessed in terms of sustainability against the likely longer time for waste stabilisation at capped above water table sites.

6.8 Risk Assessment Requirements

It is not possible to carry out a standard groundwater risk assessment for hydraulically contained sites. This is because there should be no significant leakage out of the site and so no theoretical risk. LandSim, the Agency approved landfill risk assessment software cannot be used for the same reason.

Based on this review of issues for hydraulically contained sites, a groundwater risk assessment needs to examine the following issues:

- The risk of groundwater contamination from net diffusional movement of contaminants through the liner. This assessment needs to consider groundwater flow in the opposite direction and attenuation of ammonia and organic contaminants in the liner.
- The risk of leachate leakage out of the site during periods of non hydraulic containment either through seasonal fluctuations in potentiometric levels or failure of leachate extraction systems.

- The impact of any groundwater ingress on any local water resources.
- The likely time to reach waste stabilisation assuming a declining source term and the total of cap infiltration and groundwater ingress.
- The capacity of the lining systems to minimise impacts to groundwater on eventual cessation of leachate extraction.

6.9 Comparison of Advantages & Disadvantages of Hydraulic Containment

Table 6.2 presents a summary of the advantages and disadvantages of hydraulically contained sites when compared to above water table landfills.

Table 6.2 Comparison of Advantages & Disadvantages of Hydraulic Containment

Issues	**Hydraulically Contained**	**Above Water Table**
Advantages		
Leachate Migration	Not possible	Occurs at all sites, requires low permeability barrier to minimise
Waste Stabilisation	Possibly more rapid even when capped.	Slow when capped and without recirculation of treated leachate.
	Depends upon depth of saturated waste and how inflowing groundwater moves to leachate collection systems. Research needed.	
Risk of Groundwater Contamination	Unlikely (but check diffusion out versus inflow in)	Possible
Groundwater Monitoring: quality	Not strictly necessary as no movement of leachate, depends on predicted net diffusional outflow	Vital to ensure not contamination moving away from landfill
Leachate Generation	Increased by groundwater Ingress	Reduced by leakage through base
Leachate Pumping and Treatment	Increased volumes due to groundwater ingress	Reduced by leakage through base
Depth of Base of Site	Not limited by technique	Limited by depth to water table
Leachate Extraction Systems	Variable, depends on depth of saturated waste. Required for life of site.	High density required to keep leachate head down everywhere for life of site.
Low Permeability Barrier	Useful but not theoretically essential. More important for additional safety and site closure. Requirement of the Landfill Directive.	Essential. Requirement of the Landfill Directive.
Failure of lining system	Less likely because mineral liners kept moist. Consequence of failure is minimal due to gradient onto the site.	Consequence could be significant as gradient is out of the site.
Land take for disposal capacity	Deeper landfills will use less land than shallow landfills.	See Opposite.
Disadvantages		
Groundwater Control	Required during construction and operation	Not necessary
Level of Operator Skill	Needs skilled operation / flexibility	Well understood
Groundwater Monitoring: levels	Need detailed and well planned monitoring.	Only limited information needed
	Need to respond to changes in levels	
Other Differences		
Leachate levels	Require control and reliable measurement	Require control of small head on liner

7. Conclusions

7.1 General

Hydraulic containment, operating a landfill such that leachate levels are maintained below the water table outside the landfill, is a realistic option for particular landfill sites.

The successful operation of a hydraulically contained landfill, does however, require greater knowledge and operational control than a conventional above water table containment landfill site.

7.2 Hydraulic Containment in the UK

- Hydraulic containment, as a landfill strategy, is poorly understood by regulators and landfill operators in the UK. The application of the law and associated guidance available for operators tend to avoid the issue. However, neither legislation nor guidance rules out the use of hydraulic containment.
- The concept of hydraulic containment is noted in the literature and is in use in North America.
- Entec has identified 27 hydraulically contained landfills and postulate that there may be 40 or 50 in existence in the UK. Most of those identified are in southern and eastern England.
- Hydraulic containment appears to be operated in a range of different settings including major, minor and non aquifers. There are a significant number of sites within Jurassic Clay strata and this may be a function of the infilling of clay-pits with naturally shallow water tables and licensed leachate levels historically set to avoid leachate breakout at the surface. There are also a number of sites within sand and gravel deposits and one probable site within the Sherwood Sandstone.
- Only three landfills in the UK were identified which pursue a strategy of maintaining a robust pressure differential (more than 10 m) between leachate heads and the water table ensuring containment at all parts of the landfill even when seasonal and climatic groundwater level variation occur.
- Groundwater ingress is clearly occurring at a number of sites. The rate of ingress per unit area of landfill appears to depend on the difference between leachate and potentiometric levels, but also the hydraulic conductivity of the basal and side slope liners or natural strata where no lining is present.
- A variety of landfill lining systems are currently in use at the surveyed landfill sites. It is of note that the highest rate of groundwater ingress is at a site with a composite HDPE over clay liner. The main reason for ingress being the lack of engineered side slope lining.

- Impacts on groundwater have not been observed at any of the above landfills with the exception of instances of surface breakout.
- The lack of impacts on groundwater suggests that hydraulic containment is an effective means of controlling leachate migration from landfills. In the right conditions, hydraulic containment may be considered preferable to above water table landfills. Unlike above water table landfills, hydraulically contained sites, if operated correctly, do not impact groundwater.
- There are a number of aspects of the design of a hydraulically contained site that require assessment. Guidance is given here on a number of these aspects, including the approach for groundwater risk assessments.

The conclusions presented above are based on limited information, in spite of the effort made by Entec to locate and investigate all hydraulically contained landfills. It is also true that the engineered landfills of the UK (above or below water table) are not old enough to draw conclusions about the long-term behaviour. Entec recommend that further research be carried out in two areas: location of any other hydraulically contained landfills and more detailed monitoring around existing landfills to fully understand the hydraulic pressure regimes.

8. Recommendations

8.1 Research Sites

There is a clear need for research or example sites in which the principals and practicalities of hydraulic containment can be investigated over the medium to long term. The sites need to have the co-operation and input from both landfill operators and the regulators so that all parties have confidence in the quality of the research and the results produced.

Suitable sites could include:

- a site in clay-rich formation;
- a site in sands and gravels;
- a site which has a lot of groundwater ingress (to allow the impact of this on waste stabilisation to be assessed).

For each type of site, the preference would be for a site with a long history of being hydraulically contained.

At each site, it would be prudent to examine the following factors:

- evidence of groundwater contamination;
- leachate quality and waste stabilisation;
- rates of gas production;
- leachate extraction rates and estimation of groundwater ingress;
- developed practices during engineering;
- leachate pumping costs and energy consumption;

8.2 Waste Compaction

A factor which may affect the long-term performance of hydraulically contained landfill sites is the reduction in permeability of the lower parts of the waste pile over time. Such a reduction could lead to increase perching of leachate, and accumulation of leachate against the barrier in areas above the water table. Research is needed to determine whether this occurs and, if it does, how quickly permeability of the waste is reduced over time. Geophysics has been used successfully to identify the location of perched water levels within landfills and further research into this technique is required.

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Appendix A
Questionnaire Q1

2 Pages

Entrust Research Project - Ref 760828.012

REVIEW OF THE PERFORMANCE OF HYDRAULICALLY CONTAINED LANDFILLS

Entec has obtained funding for a research project to investigate the number of Landfills in the UK which use hydraulic containment as part of a leachate control strategy and how well they perform. Hydraulic containment requires a sub-water table landfill with the maintenance of leachate heads at a level lower than those in the surrounding groundwater.

Q19456/01 QUESTIONNAIRE FOR ENVIRONMENT AGENCY REGIONS

1

EA Region:			
Name:		Tel No.	
Position:		Date:	

The first phase of the above project is to identify the number of sub-water table landfills that exist within the UK. This includes operational, closed and proposed landfills. Entec would be grateful if you could fill in the Tables below for your Environment Agency Region.

2 Number of Operational Landfills

Working Method	Licence Status	Number of Sites		
		Non Inert Waste	Inert Waste Only	Total
Sub-water table operation	Waste Man Licence			
Currently dewatered, but will revert to sub-water table on completion	Waste Man Licence			

3 Number of Proposed Landfills

Working Method	Licence Status	Number of Sites		
		Non-Inert Waste	Inert Waste Only	Total
Proposed dewatered, but will revert to sub-water table on completion	To be licensed			

4 Number of Closed Landfills

Working Method	Licence Status	Number of Sites		
		Non-Inert Waste	Inert Waste Only	Total
Sub-water table (leachate pumped)	Unlicensed			
Sub-water table (leachate not pumped)	Unlicensed			

5 Please enclose lists of the names, locations and operators of the landfills listed above

A form has been provided for convenience but if computer printout does not fit the format exactly, please send the printout

REVIEW OF THE PERFORMANCE OF HYDRAULICALLY CONTAINED LANDFILLS

Entec has obtained funding for a research project to investigate the number of Landfills in the UK

5

Landfill Name	Landfill Operator	Type/Comment (See Below)	Address

O = Operational
P = Proposed
C = Closed

Appendix B
Questionnaire Q2

2 Pages

Entrust Research Project - Ref 760828.012

REVIEW OF THE PERFORMANCE OF HYDRAULICALLY CONTAINED LANDFILLS

Entec has obtained funding for a research project to investigate the number of Landfills in the UK which use hydraulic containment as part of a leachate control strategy and how well they perform. Hydraulic containment requires a sub-water table landfill with the maintenance of leachate heads at a level lower than those in the surrounding groundwater.

Q19456/02 Questionnaire for Landfill Operators

Operator:

Site Name:

Location:

NGR:

Status: Operational ☐ Proposed ☐ Closed ☐

Dates of Operation: from 19_____ to 19_____

Waste Management Licence Number:

Area of Site (approximate):

Average Thickness of Waste (approximate):

Type of Waste: Inert ☐ Non-inert ☐

Geology (brief description):

Is the Site Lined? Yes ☐ No ☐

Type of Liner(s) (brief description):

Is the Site Capped? Yes ☐ No ☐

Type of Cap (brief description):

Leachate Drainage/Collection System (brief description):

Is Leachate Pumped from the Site? Yes ☐ No ☐

Quantity of Leachate Pumped:

Leachate Levels: _____________ m AOD____________ m above base of site

Groundwater Level in Surrounding Strata:

______ m AOD _____ m below ground level

Is groundwater pumped? Yes ☐ No ☐

Is Leachate Quality Monitored? Yes ☐ No ☐

Frequency of Monitoring:

Is Groundwater Quality Monitored? Yes ☐ No ☐

Frequency of Monitoring:

Are You Willing to Provide Further Data for This Site? Yes ☐ No ☐

Contact Name: Telephone No:

Any Other Comments:

Appendix C
Site Descriptions

18 Pages

Entec

This Appendix contains descriptions of the 18 landfills identified through the search process as being hydraulically contained. Much of the information used to compile these brief descriptions was provided by the operator on the understanding that site name would not be identified and sites are only identified by a letter (A to R).

Site A

This landfill site was formerly a quarry into which cement kiln dust (CKD) had been landfilled in conjunction with domestic refuse. It now accepts only domestic, commercial and industrial waste. The site has a capacity of 5 000 000 m^3. It does not have basal drainage and is not lined (i.e. natural containment). The site is approximately 80% filled with a 35 m maximum thickness of waste. It is approximately 500 m in length and 700 m in width. It was originally split into two cells (North and South) with a low internal bund; the exact dimensions of this bund are not known.

The Southern cell has been completely filled and is no longer active. This cell contained two discrete areas; one area is composed of 50% CKD and 50% refuse; and the other area is made up of 90% CKD and 10% refuse, with two long trenches of 100% refuse. The Northern cell also has two discrete areas; one area is composed of 50% CKD and 50% refuse; the other area, which is the active part of the site, contains 100% refuse.

The site sits in a 55 m thick Kimmeridge Clay layer, which overlies the Corallian Limestone. Groundwater in the limestone is artesian with a piezometric head at approximately +52 m AOD. There is also a 1m layer of sand and gravel deposits above the Kimmeridge Clay with a groundwater head of approximately +55 m AOD. The maximum height of waste is at +50 m AOD. The leachate levels within the site are approximately +30 m AOD, but there are areas of perched leachate within the CKD at levels up to +35 m AOD; the low permeability of the CKD inhibits the free movement of leachate. Leachate levels are overall slightly lower within the zone of 100% refuse in the Northern cell and there is, therefore, some flow of leachate from the Southern cell into the Northern cell.

The volume of leachate pumped to maintain hydraulic containment is of the order of 3 200 m^3/a. There are 19 leachate monitoring boreholes in the CKD filled zones of the site and 8 within the refuse filled zone. The level and quality of the leachate is monitored in each of the 19 boreholes. The leachate within the 100% refuse zone is typical of domestic refuse, with an average ammonia concentration of 200 mg/l. The leachate within the CKD zone is very alkaline in nature, with a pH of up to 13.

There is a total of 35 monitoring boreholes around the site in the surrounding area, 32 screened in the Kimmeridge Clay and 3 screened in the Corallian Limestone. A suite of groundwater quality parameters (i.e. pH, ammonia, chloride, BOD, COD, sulphate, nitrate, metals, etc) are monitored routinely in all of these boreholes. The groundwater quality in the Corallian Limestone is poor (heavily mineralised), but there is no evidence of any contamination from the landfill site in either the Kimmeridge Clay or Corallian Limestone. There are no nearby groundwater abstractions. There is a surface watercourse at the site boundary, but again there have been no contamination incidents from the landfill.

Site B

This site is a recent development and was opened in 1997. It was previously a greenfield site in an agricultural area. It accepts inert, household, commercial and industrial wastes; there are no special wastes deposited. The site sits in Mercia Mudstone (formerly Keuper Marl) with the Sherwood Sandstone aquifer 193 m underneath. There is periglacial clay cover on one side of the site, separated from the landfill by 10 m of outcropping Mercia Mudstone.

The site is approximately 600 m in length and 400 m in width and it is lined with a 1 m thick layer of reworked Mercia Mudstone. It is expected that the site will be divided into 15 cells. There is currently one cell filled, capped and restored, one cell has been filled but is uncapped, one operational cell and one cell is under construction. The thickness of waste varies between 14 and 18 m. The depth of the base of the site is 4 m bgl (+4 m AOD) in the capped cell and the depth of the base of the site in the remaining cells is approximately 10 m bgl (-2 m AOD). The material excavated in the construction of cells is used in the capping and restoration of filled cells.

The cells are separated by low internal bunds which rise to 2 m from the base of the site. The top of these bunds are +6 m AOD in the capped cell and 0 m AOD in the other cells. The leachate levels are maintained at a level below these bunds by pumping to a lagoon and the leachate is periodically tankered off site. There is a borehole in each cell to facilitate the extraction of the leachate; these boreholes are also used to monitor the leachate levels and quality. The leachate quality is typical of that from household and commercial waste. A typical suite of leachate parameters (i.e. pH, ammonia, chloride, BOD, COD, sulphate, nitrate, metals, etc) are monitored routinely.

Six boreholes are used to monitor the groundwater levels and quality in the vicinity of the site. They are all within the site boundary and are positioned in both the Mercia Mudstone and the periglacial material. The groundwater level is approximately +7.5 m AOD and varies by approximately 1 m across the site; there is no significant seasonal variation in groundwater levels. Background groundwater quality is good. The nearest down gradient groundwater abstraction is 2 500 m away; and is situated in a superficial sand and gravel within the periglacial layer. The nearest surface watercourses include agricultural irrigation ponds and a small watercourse close to the site boundary. There are no areas of special scientific interest near the site.

A typical suite of surface water and groundwater parameters (i.e. pH, ammonia, chloride, BOD, COD, sulphate, nitrate, metals, etc) are monitored routinely. There has been no evidence of any contamination from the landfill site. To date no Groundwater Risk Assessment (Regulation 15) has been carried out for the site.

Site C

The site accepts household, commercial, industrial, inert and liquid wastes. It sits in Mercia Mudstone with an average thickness 20 m, overlying a carbonaceous coal layer. It is 800 m long and 50 m wide and is nominally divided into nine cells. However, there is no significant hydraulic separation between the cells and so the landfill can be thought of as a single unit. The site is approximately 75-80% filled.

The site is cut approximately 8 m into the side of a hill and its design is such that on completion it will be raised by 42 m above the current ground level. The thickness of the waste ranges from 10 m at the edge of the site to 50 m at the middle. The base of the waste is at 0 m AOD.

The leachate is collected via drainage channels in the base of the site and recirculated to the top of the site from eight boreholes. The leachate level and quality is monitored in each of the boreholes. The leachate levels are maintained at approximately 1 m above the base of the site (+1 m AOD), but there are some areas of perched leachate resulting from recirculation.

The groundwater levels and quality are monitored in six boreholes in the carbonaceous layer. The groundwater levels vary from +8 m AOD to +10 m AOD across the site and are close to ground level. A typical suite of surface water and groundwater parameters (i.e. pH, ammonia, chloride, BOD, COD, sulphate, nitrate, metals, etc) are monitored routinely. The background groundwater quality is very poor in the carbonaceous coal layer, as it is heavily mineralised. There are no nearby groundwater abstraction points and there is no evidence of any contamination of the groundwater from the landfill.

There is a watercourse on the perimeter of the site, which is considered to have poor water quality as a result of industrial activity in the area. There has been one recent breakout of leachate to surface waters; however it was contained in a lagoon and did not enter the watercourse.

Site D

This landfill site was formerly a sand and gravel quarry and now accepts industrial, commercial, inert and non-putrescent waste. It is approximately 300 m long and 250 m wide. The landfill sits in a Sand and Gravel deposit that overlies the London Clay. The site is lined with 1 m of engineered clay. It is divided into three cells of approximately equal size; these cells are divided by internal bunds that are approximately 2 m in height.

The volume of leachate pumped to maintain hydraulic containment is of the order of 4400 m^3/a. The leachate levels are maintained at 1m above the base of the site (+69.5 m AOD). The leachate is collected by a herring bone drainage 'blanket' in the base of the site and pumped from nine boreholes to a storage tank. The leachate quality is monitored in five of these boreholes. There was, however, no pumping of leachate during the initial operation of the site. The leachate levels reached a maximum of 4.5 m from the base of the site and this has led to some movement of leachate between the cells.

The groundwater level is approximately +71 m AOD and is monitored in 18 boreholes around the site; these are situated at a distance of zero to 1500 meters from the site boundary. The levels vary considerably (circa 2.5 m) seasonally and also vary across the site. The groundwater quality is monitored in 16 of these boreholes; a typical suite of analyses (i.e. pH, alkalinity, nitrate, sulphate, COD, ammonia chloride, metals, etc) is carried out quarterly. The background groundwater quality is good and there is a groundwater abstraction for public water supply approximately 2000 m down gradient of the landfill. There are a series of drainage ditches on the site boundary, which are linked to a nearby stream. There has been no evidence of contamination from the landfill to the surface water systems or to the groundwater.

Site E

This site is now closed; it was developed from a quarrying operation and accepted industrial and commercial waste. The geology of the area is Quaternary Drift deposits; it sits in a Sand and Gravel layer with underlying Tertiary Clay. It is lined with 1m of engineered clay and is not divided into cells. It covers approximately 6.0 hectares and the thickness of the waste is approximately 40 m.

The volume of leachate pumped in order to maintain hydraulic containment is of the order 11 000 m^3/a. The leachate levels are maintained at 21 m above the base of the site (+10 m AOD) by pumping from 11 boreholes to foul sewer. These are all newly drilled boreholes, as the original boreholes had become blocked. Leachate quality has been monitored since 1998 in six of these boreholes.

The groundwater levels are approximately 2 m bgl (+19 m AOD) and are monitored in 16 boreholes, which are situated at a distance of 70 m to 1600 m from the site boundary. There is approximately 1.5 m variation in level with season but very little variation across the site as the terrain is quite flat. The groundwater quality is also monitored quarterly in these boreholes; a typical suite of analyses (i.e. pH, alkalinity, nitrate, sulphate, COD, ammonia chloride, metals, etc) is carried out. The background groundwater quality is good and the nearest down gradient groundwater abstraction point 2200 m away. The nearest surface watercourse is a series of drainage ditches on the site boundary, which are linked to a nearby stream. There has been no evidence of contamination from the landfill to the surface water systems of the groundwater system.

Site F

This site is approximately 500 m by 500 m in area. It accepts industrial, municipal, commercial and some types of special waste (mainly asbestos). The landfill sits in Lias Clay, which is greater than 30 m in thickness. The site is not lined but a full groundwater risk assessment of the site was carried out as part of a planned site extension.

The landfill is not divided into cells, but does have some low internal bunds. The leachate is collected via stone drains along the centre of the site. The design was such that hydraulic containment of the site would be maintained by pumping the leachate from the zone between an internal bund and the landfill boundary. The leachate levels at the edge of the site would be maintained at +43 m AOD and the surrounding groundwater levels are at +44 m AOD. The leachate levels in the centre on the site would be higher than the surrounding groundwater levels; this would minimise the amount of leachate pumped out of the landfill. The site operated on this philosophy but it was discovered that the site 'clipped' a permeable layer. The leachate is now also pumped from the centre of the landfill site (i.e. inside the internal bunds) via the gas collection system. This has resulted in an increase in the volume of leachate pumped.

There are now a total of 20 boreholes monitoring leachate levels within the site and leachate quality is monitored in 15 of these. Groundwater levels and quality are monitored in 3 boreholes within the site perimeter. The background groundwater quality is considered to be good and there are no nearby down gradient groundwater abstraction points. There is a stream that runs around the perimeter of the site. There have been no contamination incidents from the landfill site to the groundwater or to surface waters.

Site G

Site G accepts commercial, municipal, industrial and some special waste. A geological survey in 1988 concluded that the site presented a low risk to groundwater and as a result a Regulation 15 groundwater risk assessment has not been undertaken. The site sits in Alluvial Silts and Clay (2-20m thick) overlying Lias Clay/Limestone. The site is lined with a composite clay and HDPE liner.

The site is approximately 400 m long and 400 m wide. The base of the site is 2.5 m below the original ground level and the waste thickness ranges from 2.5 m thick at the site edge to 10 m thick in the centre. It is expected to have 11–12 cells, when completed. These cells are 400 m long and 30 m wide and it is currently 60% filled. Each cell has a central drainage ditch; these ditches are connected to five leachate-pumping boreholes, which maintain the leachate within the landfill at a constant +2 m AOD level. There are, however, some areas of perched leachate at a level of +4 m AOD. The five leachate-pumping stations pump a volume of approximately 35 000 m^3 per annum of leachate to an effluent treatment works; the treated effluent is then discharged to a tidal estuary. The leachate levels and quality are monitored in 10 boreholes in the restored area and more are planned for active areas.

The seasonal groundwater levels vary considerably. The level is 5 m below the base of the site (-0.5 m AOD) during the summer and so the landfill is not sub-water table during the summer period. However, the groundwater levels in winter are at ground level and so the site is hydraulically contained. There is an above ground bund around the site to prevent flooding of the site in winter. The background groundwater quality in the surrounding area is quite poor as the region is reclaimed from the sea. There are no nearby groundwater abstraction points. Three boreholes within the perimeter of the site monitor the groundwater levels and quality. The groundwater quality parameters analysed include ammonia, BOD, suspended solids, nitrates and the Red List substances and metals; there is no evidence of any groundwater contamination from the landfill site.

There are some ditches on the site perimeter, which are connected to a river. There is a County designated wildlife area in the vicinity. There have been no contamination incidents to the surface waters from the landfill site.

Site H

This site was formerly on old brick quarry; it now accepts commercial, industrial and municipal wastes. It is 150 m in length and 150 m in width. The site is cut 18 m into Mercia Mudstone (Keuper Marl) which is 35 m thick. There is a permeable layer approximately 5 m below the base of the site, which is artesian in nature.

The site is divided into two cells of approximate equal size; one cell (phases 1-3) has been filled, but not capped and the other cell (phase 4) is currently active and is approximately 25% full. The base of both cells has been lined; the side of the active cell has been lined with a 1.5 m layer of clay; however the sides of the completed cell are not lined. Gravel drains conduct leachate to a vertical borehole pump in cell one; and cell two has perforated pipe leading to an inclined borehole pump.

The groundwater levels in the Mercia Mudstone are 2.5 m bgl (+15.5 m AOD) and there is a small spring feeding directly into the filled cell. The underlying artesian layer has a head greater than +23 m AOD. The background groundwater quality is good.

The volume of leachate pumped to maintain hydraulic containment is of the order 80 000 m^3/a. The leachate levels are maintained at approximately 8 m above the base of the waste (+8 m AOD) and the pumped leachate is discharged to public sewer. Leachate levels are slightly higher in the completed cell than in the active cell. Consideration is being given to allowing the leachate levels to rise to approximately 12 m above the base of site sometime in the future. This would still be approximately 3.5 m below the surrounding groundwater levels. The leachate levels and quality are monitored in the two leachate-pumping boreholes.

The groundwater levels and quality are monitored by four boreholes in the Mercia Mudstone and one borehole in the artesian layer. These are all located within the perimeter of the site. A typical suite of analyses (i.e. pH, alkalinity, nitrate, sulphate, COD, ammonia chloride, metals, etc) is carried out annually and ammonia, BOD and suspended solid analyses are carried out quarterly. A licensed groundwater abstraction point in the old brickworks approximately 20 m from the landfill is not currently in use. There is a surface watercourse on the perimeter of the site. There is no evidence of any groundwater contamination from the landfill site to the groundwater or to the surface waters.

Site I

This sub-water table landfill site sits adjacent to a larger dilute-and-disperse landfill site. The dilute and disperse site was originally a local authority site and is believed to have begun operation sometime in the late 1940s. It has accepted many types of waste through the years including municipal, commercial, industrial and inert waste, but is not currently active. The dilute and disperse landfill covers approximately three times the area of the containment landfill.

The sub-water table part of the landfill accepts commercial, municipal, special (asbestos), liquid, difficult and inert waste. The site is divided into 12 cells and the sides and base of the site are lined with clay. There is no information on the dimensions of the inter-cell bunds.

The base of both the dilute and disperse site and the sub-water table site are in a layer of Lias Clay which is underlain by Limestone/Marl. There are two major aquifers in the region, however it is believed that neither is in hydraulic continuity with the site due to the substantial thickness of the clay formations.

The leachate levels are maintained at approximately +103 m AOD by pumping and recirculating. The groundwater levels are approximately +120 to +130 m AOD.

There are a number of groundwater monitoring boreholes on the boundary of the site and the levels of dissolved oxygen, pH, chloride and ammonia in samples from these boreholes are analysed monthly and a fuller suite of analyses carried out annually. There have been some problems with the groundwater quality in the boreholes on the site boundary, but this has been attributed to the dilute and disperse site rather than the sub-water table site. The background groundwater quality in the area is considered poor due to contamination from an old mine-working. The nearest down-gradient surface watercourse is a reservoir, which is approximately 2000 m from the site boundary. There has been no evidence of any contamination from the hydraulically contained landfill.

Site J

This sub-water table landfill site is made up of two separate parts, Zone A and Zone B, which both sit in a larger dilute and disperse landfill site. The dilute-and-disperse site was originally a local authority site and is believed to have begun operation sometime in the late 1940s. It has accepted many types of waste through the years and these include municipal, commercial, industrial and inert waste. The dilute and disperse site is currently active, but accepts only inert material for reclamation purposes.

The whole site sits in Lias Clay, which is underlain by a Limestone/Marl layer. The minimum thickness of the Lias Clay layer is 15 m. There are two major aquifers in the region, however neither is in hydraulic continuity with the site area due to the substantial thickness of the clay formations.

Zone A is approximately 200 m in length and 100 m in width. It is separated from the dilute-and-disperse site by a clay liner at the base and sides. It is not divided into cells. It has accepted commercial, municipal, special (asbestos), liquid and inert waste and is now complete but uncapped. The leachate level is maintained at approximately +66 m AOD by pumping from a sump in the middle of the zone. The leachate was recirculated when the site was in operation, but now is tankered to Zone B.

Zone B is approximately 600 m in length and 500 m in width and is lined. It is divided into six equal size cells, with a low bund of height 3-4 m between the cells. The site accepts municipal, commercial, industrial and inert waste. To date, one cell is completely filled and a second partially filled. The leachate levels are maintained at a level 1 m above the base of the site and recirculated. The monitoring data indicates that the leachate level in this zone is of the order +75 m AOD and it is therefore not sub-water table.

The groundwater levels around the site are approximately +69 to +74 m AOD and they do not vary significantly with the seasons. There are 25 groundwater monitoring boreholes at the edge of the larger dilute and disperse site which monitor groundwater levels and quality. The levels of dissolved oxygen, pH, chloride and ammonia are analysed monthly and the levels of sulphate alkalinity, total organic nitrogen, total organic carbon, suspended solids and metals are analysed quarterly.

There have been some problems with the groundwater quality in the boreholes on the site boundary, but this has been attributed to the dilute and disperse site and not to the sub-water table site. The nearest downgradient surface watercourse is approximately 2000 m from the site boundary and there has been no evidence of any contamination from the hydraulically contained landfills.

Site K

This landfill site is within an old quarry, which extracted from a granodiorite intrusion overlain by a Mercia Mudstone layer. It receives 614 000 tonnes of waste per annum and is expected to be completed in 2001. It accepts municipal, commercial, industrial, special and inert wastes. There are two older dilute-and-disperse landfill sites in the same intrusion and these are within 500 m of the site. They were in operation during the 1970s and have been filled with mainly putrescible waste. A groundwater risk assessment has been carried out for this site.

The landfill covers an area of approximately 83 000 m^2 and has a maximum depth of 70 m. The base at this point is at +16 m AOD. It is not divided into cells. The leachate levels are maintained at a level between +19 and +22 m AOD and the volume of leachate, which is pumped from a sump in the centre of the landfill, is of the order of 200 000 m^3 per annum.

There are two groundwater-bearing strata around this site: Mercia Mudstone and the granodiorite. The groundwater within the Mercia Mudstone varies between +70 and +95 m AOD and is not considered to be in hydraulic contact with the granodiorite. There are no licensed groundwater abstraction points within 1500 m of the site.

There is also groundwater movement within the fractures and fissures of the granodiorite and the granodiorite is classified as a minor aquifer. The groundwater level immediately surrounding the site varies between approximately +47 to +68 m AOD and the flow is towards the central leachate pumping station in the centre of the landfill. There is also flow of groundwater from the old dilute and disperse landfills towards the hydraulically contained landfill.

The groundwater levels are monitored in 18 boreholes and the groundwater quality is monitored in 10 of these. The groundwater analyses include measurement of dissolved oxygen, pH, chloride and ammonia. There is no information available relating to the background groundwater quality or any possible contamination incidences to the groundwater or surface waters.

Site L

This landfill is a former claypit and part of the pit was infilled with construction waste in the late 1970s and early 1980s. The landfill licence for this area was surrendered before 1994. The remainder of the pit began operation as a landfill in 1983 and accepts putrescible, difficult, special, liquid and inert waste. It is 1750 m in length and 1000 m in width and the depth to the base of the site varies between 10 and 30 m. The site is divided into 11 cells, but there are only inter-cell bunds for the most recent cells. The cell dimensions are approximately 200 m by 250 m.

The site sits in Boulder Clay and Oxford Clay with a glacial channel transecting the currently unfilled south-eastern boundary. The strata underlying the site comprise around 20 m of either in situ Oxford Clay or replaced Callow (weathered Oxford Clay). This overlies a layer of Kellaways Sand and at greater depth the Great Oolite (Blisworth Limestone). A risk assessment has been carried out for the site.

The landfill was not initially designed to be hydraulically contained, but leachate is pumped to protect against surface water breakout. However, there are plans to reduce leachate levels in some areas of the site to ensure hydraulic containment. Wells will be retrofitted in the filled areas and spine drains and sumps will be used in the new cells. It is proposed that the leachate levels will be maintained at +85 m AOD in the older areas and at +75 m AOD in the new areas. The leachate levels currently vary from +92 m AOD in the older cells to +79 m AOD in the most recent cells.

The groundwater levels in the Oxford Clay are approximately +85 m AOD, but are lower, (circa +65 m AOD) immediately adjacent to the active and unfilled part of the landfill due to unloading effects. The groundwater levels also vary considerably, about 20 m, across the site but there is less than a 1m seasonal variation. The head of leachate currently exceeds the groundwater piezometric surface in the Kellaways Sands layer, which is classified as a minor aquifer. The nearest licensed abstraction point is 2500 m from the site.

There are 11 boreholes monitoring the groundwater levels and quality. These boreholes are at a distance of up to 20 m from the site boundary and some are within the site boundary. A typical suite of analyses (i.e. BOD, COD, TON, dissolved oxygen, ammonia, chloride and metals) is carried out monthly. There is no evidence of any contamination from the landfill site to the groundwater in the Oxford Clay but the background groundwater quality in this layer is poor with high concentrations of sodium, chloride and sulphates. There is also no evidence of any contamination to the groundwater in the Kellaways Sands from the landfill site but again the background quality of the groundwater in this layer ensures that it is unsuitable for most purposes without treatment. There is a surface watercourse on the site boundary, but there has been no evidence of any contamination to this watercourse from the landfill site.

Site M

This landfill is a former claypit. It has been in operation since 1983 and is currently 75% filled. It accepts putrescible, difficult, special and inert waste. It is 2 000 m in length and 1 250 m in width and the depth of the base of the site varies between +10 and +30 m AOD. The site is divided into 11 cells, but there are only inter-cell bunds for the most recent cells. The cell areas vary from 22.5 ha for the older unlined cells to 2.5 ha for the newly-engineered cells.

The site sits in the Oxford Clay and the base of the site is separated from the underlying Kellaways Sand layer by reworked Callow/Oxford Clay with an average thickness of 5 m. This is underlain by a layer of Kellaways Clay and at greater depth the Great Oolite (Blisworth Clay/Limestone). A risk assessment has been carried out for the site.

The leachate levels currently vary considerably across the site. The leachate levels in the older cells are maintained at approximately +61 m AOD and are maintained at +52 m AOD in the newer cells. The landfill was not initially designed to be hydraulically contained, but it is protected against surface water breakout. However hydraulic containment is planned and wells will be retrofitted in the filled areas and spine drains and sumps will be used in the new cells. It is planned to lower the leachate levels to +49 m AOD.

The groundwater levels in the Oxford Clay vary between +55 and +60 m AOD, but are lower, (circa +45 m AOD) immediately adjacent to the landfill due to dewatering and unloading effects. The groundwater levels vary by 5 m across the width of the site and there is 0.5 m of seasonal variation. There is a +52 m AOD groundwater piezometric surface in the Kellaways Sands layer. This is classified as a minor aquifer but the nearest licensed abstraction point is 2500 m from the site.

There are 13 boreholes monitoring the groundwater levels and 12 monitoring the groundwater quality. These boreholes are at a distance of up to 20 m from the site boundary and some are within the site boundary. A full suite of analyses (i.e. BOD, COD, and TON, dissolved oxygen, ammonia, chloride and metals) is carried out monthly. There is no evidence of any contamination from the landfill site to the groundwater in the Oxford Clay but the background groundwater quality in this layer is poor with high concentrations of sodium, chloride and sulphates. There is also no evidence of any contamination to the groundwater in the Kellaways Sands from the landfill site but again the background quality of the groundwater in this layer ensures that it is unsuitable for most purposes without treatment. There is a surface watercourse on the site boundary, but there has been no evidence of any contamination to this watercourse from the landfill site.

Site N

This landfill site is situated within a former claypit and began operation in 1997. It accepts domestic, commercial and industrial and inert waste and the site is likely to remain in operation for the next 10 years. It is 575 m in length and 425 m in width and is not divided into cells. The depth of the base of the site is approximately +41 m AOD, which is 37 m bgl. It is a containment landfill and the base and sides are lined with 1 m of engineered clay.

The strata underlying the landfill comprise Ruabon Marl of thickness 3.5 m to 41.5 m and at greater depth deposits of the Middle Coal Measures. Deposits of superficial till, river terraces and alluvium have also been encountered around the site. A risk assessment has been carried out for the site.

The leachate levels are maintained at +42.5 m AOD by recirculating the leachate, which is collected in a single sump from a herringbone leachate collection system. The groundwater in the surrounding strata is approximately +53 m AOD and varies 2m across the site. There is also a 2 to 4 m seasonal variation in groundwater levels.

There are 20 boreholes monitoring the groundwater levels at distances between 5 and 50 m from the site boundary. Groundwater quality is monitored in 19 of these boreholes. A suite of analyses (e.g. BOD, COD, TON, dissolved oxygen, ammonia, chloride and metals) is carried out monthly and quarterly. The background groundwater quality is poor with high concentrations of Fe, Mn, Cd, calcium bicarbonate, calcium sulphate and sodium sulphate. There is no evidence of any contamination of groundwater from the landfill The nearest down gradient groundwater abstraction point is 2000 m from the site.

The nearest downgradient surface watercourse is a major river approximately 100 m from the site boundary and there has been no evidence of any contamination to this watercourse from the landfill site.

Site O

This landfill is a former claypit and is 1400 m in length and 600 m in width. It accepts domestic, commercial and industrial wastes. Area A of the site was in operation between the late 1970s and the early 1990s and is completely filled. This part of the site is not an engineered site but has a substantial thickness of Oxford Clay at its base. It is not divided into cells and is capped and restored. The Waste Management Licence for this site has been surrendered.

Area B of the site is currently in operation and is approximately 60% filled. Its base is lined with 1 m of Oxford Clay and its sides are lined with 2 m of Oxford Clay. Area B will have 13 cells of approximate dimensions 140 m in length and 140 m in width on completion. The thickness of waste varies between 8 and 16 m across the site with the maximum thickness in the centre of the site.

The site sits in the Oxford Clay and the base of the site is separated from a Kellaways Sand layer, by a minimum 0.5 m thickness of Oxford Clay. This is underlain by a layer of Kellaways Clay and at greater depth the Great Oolite (Blisworth Limestone). A risk assessment has been carried out for the site.

The leachate levels currently vary considerably across the site. The leachate levels in the restored Area A are currently above the piezometric groundwater levels and so it is not hydraulically contained. The leachate levels within Area B range between +0.5 and +14.5 m AOD. The higher levels are due to areas of 'perched' leachate due to recirculation. There is a groundwater flow into the landfill and it is hydraulically contained.

The groundwater levels in the Oxford Clay are at +11 m AOD adjacent to the filled cells of the landfill, but these fall to approximately +2 m AOD in the Oxford Clay adjacent to the unfilled area. There is a pit, which is in hydraulic continuity with the Kellaways Sand, adjacent to the unfilled part of the landfill. Water is pumped from this pit to a nearby watercourse in order to control the piezometric groundwater levels in the Kellaways Sand strata. The piezometric groundwater level in the Kellaways Sand is potentially +10 m AOD but is maintained at approximately +3 m AOD in order to minimise groundwater ingress to the site.

There are 11 boreholes monitoring the groundwater levels and quality. These boreholes are at a distance of 20 m to 200 m from the site boundary. A suite of analyses (e.g. BOD, COD, TON, dissolved oxygen, ammonia, chloride and metals) is carried out monthly and quarterly. There is no evidence of any contamination from the landfill site to the groundwater in the Oxford Clay but the background groundwater quality in this layer is poor. There is also no evidence of any contamination to the groundwater in the Kellaways Sands Layer from the landfill site and the nearest down gradient groundwater abstraction points are 2000 m from the landfill site.

The nearest downgradient surface watercourse is 20 m from the site boundary, but there has been no evidence of any contamination to this watercourse from the landfill site.

Site P

This landfill is a former claypit and has been operating as a landfill since the late 1970s. It accepts putrescible, special (mainly asbestos) clinical and inert waste. Some domestic waste was also deposited on the site in the 1950s. It covers an area of 24 ha and is almost completely filled. There are plans to extend the site to a total area of 43 ha. The waste thickness varies between 20 and 30 m. The site is nominally divided into 6 cells of average cell dimensions 400 m by 150 m. The base and walls of newer cells are lined with 1 m of engineered clay, but the older cells are not lined.

The site sits in the Gault Clay and there is an underlying stratum of Gault Clay of minimum thickness 36 m, which overlies the Woburn Sands Aquifer. Formations of Lower Chalk Marl and Cambridge Greensands overlie the Gault Clay on the upgradient side of the site. There is a deep glacial channel along the upgradient side of the site and this is in hydraulic contact with a small river.

The leachate levels currently vary between +32 and +44 m AOD by removal of the leachate and pumping to the cells with the lowest leachate levels. It is planned to lower the leachate levels in the future to +37 m AOD.

The groundwater levels in the Gault Clay in the area around the site are approximately +42 m AOD. There is a net flow of groundwater towards a laterally nearby watercourse and horizontally towards the Woburn Sands Aquifer. There is a 2 m variation in seasonal groundwater levels.

There are seven boreholes monitoring the groundwater levels and quality. These boreholes are at distances between 5 and 25 m from the site boundary. A full suite of analyses (i.e. BOD, COD, TON, dissolved oxygen, ammonia, chloride and metals) is carried out monthly. The background groundwater quality in the Gault and Boulder Clay is poor with high sodium, chloride and sulphate levels. There has been no incidence of groundwater contamination from the landfill site. There is a groundwater abstraction point in the Cambridge Greensand 550 m from the site. This is separated from the landfill by a minimum 10 m thickness of Gault Clay. There is a surface watercourse approximately 100 m from the site boundary but there has been no incidence of contamination from the landfill site.

Site Q

This landfill is a former claypit and has been operating as a landfill since the late 1970s. It is approximately 90% filled and accepts domestic, industrial, commercial, difficult, special and inert waste. It formerly also accepted liquid wastes. It covers an area of 75 ha and is 1200 m in length and 650 m in width. The waste thickness varies between 20 and 30 m. The site is divided into 13 cells and the average cell dimensions are 200 m by 150 m. There are only inter-cell bunds for the most recent cells.

The site sits in the Oxford Clay and the base of the site is separated from a Kellaways Sand layer by reworked Callow/Oxford Clay. This is underlain by a layer of Kellaways Clay and at greater depth the Great Oolite (Blisworth Clay/Limestone). A risk assessment has been carried out for the site.

The leachate levels currently vary considerably across the site. The leachate levels in the older cells are maintained at approximately +43 m AOD as the landfill was not initially designed to be hydraulically contained, but it protected against surface water breakout. However hydraulic containment is planned and wells will be retrofitted in the filled areas. The newer cells are however hydraulically contained and the leachate levels are maintained at +25 m AOD.

The groundwater levels in the Oxford Clay in the area around the site are approximately +32 m AOD, but are lower immediately adjacent to the unfilled areas of the landfill due to dewatering and unloading effects. They are slightly higher in the areas adjacent to the filled areas of the landfill due to loading effects. There is less than a 1m seasonal variation in groundwater levels. There is approximately a +30 m AOD groundwater piezometric head in the Kellaways Sands layer. This is classified as a minor aquifer but there are no nearby licensed groundwater abstraction points.

There are 18 boreholes monitoring the groundwater levels and quality. These boreholes are at distances between 25 and 100 m from the site boundary. A full suite of analyses (i.e. BOD, COD, TON, dissolved oxygen, ammonia, chloride and metals) is carried out monthly. The background groundwater quality is poor with high sodium, chloride and sulphate levels. There has been one incident of groundwater contamination with high ammonia levels recorded. It is however unclear whether the landfill was the source of this contamination incident.

There is a surface watercourse on the site boundary and there have been two contamination incidences to this watercourse. These were due to leachate breakout at the surface and a diesel tanker spillage.

Site R

The hydraulically contained section of this site is an extension to an older landfill of about 6 ha area on its southern uphill side. The excavation is in the Coal Measures, which is a sequence of faulted sandstones and mudstones dipping to the southeast. Two particular sandstone beds (Keele Beds and the Enville Beds) are minor aquifers. There are two licensed abstractions about a kilometre down-gradient.

Ground level at the site falls from 165 m AOD in the south to 150 m AOD in the north. The groundwater level similarly falls from 161 m AOD down to 147 m AOD

The base of the waste is at 150 m AOD in the southwest falling to 134 m AOD in the north. The base of the waste is therefore 11 m to 13 m below water table. The liner is 1m of engineered clay. The leachate management strategy will be to maintain leachate heads at most 2 m above the base of waste, which is 4 m below the groundwater level. Where the sandstone at the base of the Keele Beds outcrops (in the centre of the site, Area 3), the excavation will be much shallower and an unsaturated zone is planned.