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Improving yields from vertical landfill wells through better design, installation and maintenance

by

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ABSTRACT

SCHOOL OF CIVIL ENGINEERING AND THE ENVIRONMENT

Doctor of Philosophy

IMPROVING YIELDS FROM VERTICAL LANDFILL WELLS THROUGH BETTER DESIGN, INSTALLATION AND MAINTENANCE

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In older landfills or where basal drainage systems have failed, vertical wells may be the only economical means of extracting leachate from waste. A examination of 76 vertical leachate wells installed at 13 different landfills, describes a typical vertical well field as a number of deep, retro-fitted boreholes, drilled using a barrel auger, lined with screen and casing of diameter 140 - 200mm. Well screen materials are usually steel (with cut slots), installed with a granular filter pack. Where variations in design do exist, these do not appear to be attributable to the local waste characteristics and may not always be due to site specific design needs.

A review of published investigations and groundwater well installation practice has established what factors are know to affect the performance of vertical wells: the design and installation of the well, the low hydraulic conductivity of waste and the physical and microbial clogging of the filter pack and well screen. Down-well CCTV surveys and exhumations have shown that chemical precipitations are also common, often completely coating the well screen and closing all slots, though precipitates were generally only present in the gas zone, above the leachate table, where the closure of slots will not attribute to well losses. Smearing of ground waste and cover soils around the borehole was observed in exhumed wells drilled using a rotary barrel-auger. Pumping tests have shown that the well losses associated with drilling are, however, small, and that there is little difference in well efficiency between different drilling methods.

Over time, sediments and waste pieces may be washed into the well and will be a function of the flow velocity and the pumping regime. Accumulations of material will reduce the effective drawdown in the well. Field trials have demonstrated that removing the material using development techniques has an adverse effect on performance due to the invasion of soils into the filter pack. When designing new wells for use in a landfill, a compromise may have to be made between a design that limits well losses, a design that prevents fine-grained material from being washed into the well, and one that is not prone to microbial clogging. Rules used in the groundwater industry for selecting filter packs and well screens, may, therefore, not be suitable for landfill wells, though where sulphate reducing processes are the dominant degradation mechanism, fine-grained filters can be used. If a well does become clogged with deposited sediments, then well development techniques should be avoided.

Contents

Chapter 4. Visual observations of existing wells 56

Chapter 5. Drilling methods and hydrogeological testing of new wells 76

Chapter 6. Well development 91

LIST OF FIGURES

LIST OF TABLES

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GLOSSARY OF TERMS AND ABBREVIATIONS

B	- linear head loss coefficient
BOD	- biological oxygen demand
BQ	- aquifer / formations loss
C	- non-linear head loss coefficient
CKD	- cement kiln dust
COD	- chemical oxygen demand
CQ^2	- well loss
C_u	- uniformity coefficient of a soil (D_{60}/D_{10})
D_n	- aperture through which n % of a soil sample will pass
$D_{15filter}$	- D_n of the filter material
$D_{15waste}$	- D_n of the waste
EU	- European Union
E_v	- entrance velocities
H	- total leachate head
$H_{effective}$	- effective depth
H_{sat}	- saturated depth
H_{waste}	- waste depth
HDPE	- high-density polyethylene
K	- hydraulic conductivity
mAOD	- metres above ordnance datum
mBCT	- metres below casing top
mBGL	- metres below ground level
MDPE	- medium-density polyethylene
MSW	- municipal solid waste

PSD	- particle size distribution
PVC	- polyvinyl chloride
Q	- discharge rate
Sw	- drawdown
T	- transmissivity
TOC	- total organic carbon
UK	- United Kingdom
V_w	- volume of water
V_{total}	- volume of dry solids (waste)
VFA	- volatile fatty acids

Chapter 1
Introduction

1.1 Introduction

In a contained landfill, the degradation of waste combined with the input of water will, over time, result in the release of gases and liquids (termed leachate) that may be harmful to the environment. If leachate volumes within the waste mass increase, leakage through the sides and base of a landfill is possible, with the result that surrounding land or ground and surface-water may be contaminated. To prevent the leakage of leachate, regulatory authorities will often stipulate that the leachate level within a landfill must be maintained at or below a certain limit. The volume and distribution of leachate within a landfill will also affect the rate of waste degradation, the production of landfill gas and the degree of waste settlement over time. Managing leachate within a landfill is therefore of fundamental importance if waste storage and the degradation process are to be optimised and managed safely.

In modern landfills, a leachate collection system will often be engineered into the base of the landfill during construction. The leachate collection system may include a system of underdrainage, formed of slotted pipes, drains or sumps, and vertical chimneys, raised from the base of the landfill as the waste is emplaced. The basal drainage systems and chimneys enable leachate to be removed from the landfill and conveyed to surface storage and treatment facilities.

In older landfills without a pre-built leachate collection system, or in landfills where the basal drainage system has failed or is under-performing, retro-fitted vertical extraction wells will often need to be installed. These wells are installed from the upper surface of the landfill through the waste mass. Fields of vertical wells, made up of many individual lined boreholes, may be needed to lower or control leachate levels in large sites. As many older landfills were constructed without a containment liner, an efficient leachate extraction system that prevents leakage to the environment is especially important. At such sites, vertical wells may be the only economical form of leachate management available.

Both basal drainage systems and retro-fitted wells will be expected to perform efficiently and with minimal servicing over substantial periods of time. Much research has been conducted into the design and suitability of basal drainage systems (e.g. Brune *et al.* (1991); Rowe *et al.* (2005)), with exhumations of drainage gravels, simulated laboratory tests and theoretical analysis. Appreciation of the mechanisms of clogging, through microbial and chemical processes, sedimentation and compaction, and their effects on the performance and life of drainage systems are becoming more recognised. Although there has been some research on the performance of wells in landfills (e.g., Friend and Hock, 1998, Powrie and Beaven, 2003), and the use of vertical wells in determining waste properties (Giardi, 1997, Burrows, 1998), currently no guidance exists to aid in leachate well design and operation.

It is well established in the groundwater industry that an understanding of the effects of drilling (smearing, compaction), well design (screen type and filter pack size) and maintenance schedule (well development), is essential in maximising yields from the local geological conditions. Yet, despite much anecdotal evidence of the poor performance of vertical wells, and the clogging of well bores, basic well construction and maintenance rules, common place in the groundwater industry, are rarely followed when installing and managing leachate wells.

The aims of this thesis are to:

1) develop a better understanding of the problems associated with vertical wells in landfills, and
2) determine through field trials on existing and new landfill wells, whether the performance and long term yields in new wells may be improved by adapting design, installation and development methods from the groundwater industry.

The thesis has developed through field research at a number of UK landfills, and from past landfill well data. Both land-*raise* and land-*fill* sites are included in the study, and wastes of different age and type are discussed. Although the study sites may differ somewhat in size, waste age and type, and in operational practice, the sites were chosen to be comparable in terms of waste properties (e.g. hydraulic conductivity, saturated depth). The thesis is primarily UK focused, though the implications of the research in a wider context will be investigated.

1.2 Objectives

The objectives of the research are:

- to determine the limitations of using vertical wells in landfill drainage.
- to investigate the potential clogging mechanisms in vertical leachate wells that may lead to performance deterioration and sedimentation in the well bore,
- to investigate whether established techniques used in the groundwater industry are applicable to the installation of wells in landfills,
- to use field tests to assess the effects and application of different installation techniques and well designs, and,
- to investigate the use and effectiveness of well development in maintaining and remediating leachate wells.

1.3 Thesis outline:

Chapter 1. Introduction

Chapter 2. Review of existing well designs and installation methods.
In this chapter, a review of existing vertical leachate extraction wells is carried out, with reference to a database of collated landfill well information. A summary of the common leachate well designs, materials and installation methods is given. Comparisons of designs between sites and some performance data is presented.

Chapter 3. Factors known to affect well performance.
In this chapter, the possible causes of well ineffectiveness and deterioration are discussed. Well hydraulics and how the design of a well can affect performance are examined. The current knowledge of waste hydraulics is reviewed to determine to what extent waste compaction and degradation can affect well yields over time. The processes of biodegradation and leachate generation are examined, and the mechanisms of microbial and physical clogging and how these could affect the performance of a vertical well are discussed. The methods used in the groundwater industry to develop

new wells and remediate failing wells are discussed in the context of applying them to wells in landfills.

Chapter 4. Visual observations of existing wells

A programme of field investigations of existing pumped leachate wells are described in this chapter. The investigations include down-hole CCTV surveys of a number of wells at different sites, and the exhumation of three wells from one site to observe the condition of the inner and outer casing and filter pack.

Chapter 5. Drilling methods and hydrogeological testing of new wells

In this chapter, a trial to assess the applicability of different well drilling techniques will be discussed. Hydrogeological pumping tests, used to determine well performance characteristics and to make comparisons between the different installation types, are discussed.

Chapter 6. Well development

Well development trials at two landfill sites are described. The development trials were carried out to determine the applicability and effectiveness of well development in commissioning and remediating landfill wells and to collect well bore sediments for analysis. Long-term monitoring data and hydrogeological pumping tests were carried out in the developed wells to quantify changes in performance. The results and analysis of the pumping tests are presented and discussed.

Chapter 7. Installation of new wells in landfill

The installation of new leachate wells, designed on a *site specific* basis, are described. The new wells are characterised in terms of performance and effectiveness at preventing material ingress, and compared to existing leachate wells.

Chapter 8. Discussion

In this chapter, the key findings of the research and field investigations will be discussed. Conclusions are drawn as to the best available practice of installing and maintaining vertical wells in landfill. Suggestions for further research are made.

Chapter 2

Review of existing well designs and installation methods

2. 1 Introduction to chapter

When waste is first deposited, it may contain some water but will not be saturated. This is termed the original water content and is defined as the ratio of the mass / volume of water to the mass / volume of dry solids (often, V_w/V_{total}) (e.g. Knox, 1991). The original water content will vary somewhat due to waste type and climate. Qasim and Chiang (1995), for example, give values ranging from 10 to 20 percent by volume. After landfilling, with the input of further water through infiltration and precipitation, the water content of the waste will increase due to the absorptive capacity of components such as paper, cardboard and textiles, and free draining water may get caught in traps and pockets. When the waste reaches its total absorptive capacity, the addition of any further water will lead to the production of an equivalent volume of free-draining pore water, which will move downward under the influence of gravity (Knox, 1991). When no further water can be held or absorbed by the waste, it will have reached field capacity and any further water will drain downwards to a leachate table, below which the waste is saturated. Qasim and Chiang (1995), give values of between 20 and 35 percent by volume for the field capacity of MSW (municipal solid waste). Some channelling may also occur, so that not all water input will be absorbed by the waste before it reaches field capacity.

In a contained landfill, and in the absence of controlled leachate extraction, the continued input of water will result in a rise in the leachate table to form a zone of substantially saturated waste within the landfill. As pressure heads acting on the landfill base and sides increase, the potential for leakage from the landfill will also increase. In some instances, especially in raised landfills, leachate may issue from the landfill surface to form puddles and seepage faces. As well as the potential for environmental contamination, the build-up of leachate within the landfill mass can lead to problems with stability and an increased risk of slope failure (Oweis, 1995).

The controlled management of leachate is also a legal requirement under the European Union Landfill Directive (EEC/1999/31/EC) (Environment Agency, 2006), which sets standards of landfilling across Europe through specific requirements in the design and operation of landfills. The Landfill Directive is implemented in England and Wales via the Pollution Prevention Control (PPC) Regulations 2000 and the Landfill (England and Wales) Regulations 2002.

Landfill operators are required to meet the leachate control and monitoring requirements of the legislation, and in particular Regulations 14 and 15, and Schedule III. Specifically, this includes the requirement to:

- control and monitor leachate,
- demonstrate compliance with the Groundwater Control and Trigger level requirements of Schedule III of the regulations,
- indicate whether further investigation is required and, where the risks are unacceptable, the need for measures to prevent, reduce and remove pollution by leachate,
- identify when a site no longer presents a significant risk of pollution or harm to human health (Environment Agency, 2006).

In most modern landfills, the volume of free leachate in the waste mass is controlled using a leachate collection system. This is usually engineered as part of the liner design, and may include chimneys, underlying drains and terraced slopes, which are gravity fed to one or more collection points. In older landfills without a pre-built leachate collection system, or in landfills where the basal drainage system has failed or is under-performing, vertical extraction wells will often need to be retro-fitted by installation from the upper surface through the waste mass. Retro-fitted vertical wells will be the focus of this dissertation.

Generally, vertical wells will form part of a site-wide leachate management system consisting of a means of extracting leachate, a pumping system to transport leachate around a site, a leachate treatment plant and a disposal route for leachate from the site (Last *et al*, 2004). The aims of a leachate management system will vary from site to site and may include maintaining leachate levels at or below the site licence limit, the dewatering of a site, the recirculation of leachate or the prevention of pollution. Each of these may require different volumes of leachate extraction and, perhaps, the preferential extraction of leachate from certain areas of a site. The effectiveness of a leachate management system may be measured in a variety of ways, including the reduction of observed leachate heads or basal pore water pressure within the landfill, the total volume of leachate extracted or a reduction in contamination at receptors.

Extracting leachate from waste using vertical wells often, however, proves difficult. Many landfill operators report disappointing or inconsistent yields (volume of leachate extracted over time) from both new and old wells in landfills (Burrows 1998, Powrie and Beaven, 2003). This is often attributed to the inherent heterogeneity and variability of waste from site to site and within a given site. Retro fitting wells, may, therefore be carried out on an *ad-hoc* or empirical basis with little rational design input. In a review of existing vertical wells, Powrie and Beaven (2003), compiled a database of leachate well data to investigate the current design practices of different landfill operators. Data from 54 wells located at 11 different landfills across England were collated. Information gathered included: well design, installation method, waste type and age, and pumped yields.

In this chapter, a reassessment of the Powrie and Beaven (2003) database will be made, with additional information from three sites included. A summary of the common leachate well designs, materials and installation methods will be given. Comparisons of designs between sites and some performance data will be presented. Although this thesis focuses on UK based landfill sites, specifically those in England, where data from landfill sites in other countries is considered relevant to the study, they will be included.

2.2 Vertical leachate well design types

A number of vertical leachate well types are routinely used in landfills. After Last *et al.* (2004), these can be characterised as:

1. **Massive engineering structures**. These wells are most often found in deep, vertical-sided, landfilled quarries. The full length of the well or pipe-string (a series of connected sections) is constructed from the landfill base, extending the full height to the

final restored surface. These wells allow the pumping of leachate and surface waters to continue throughout the construction, filling and restoration of the landfill.

2. **Concrete or plastic chambers**. These well chambers are formed from pre-cast concrete or plastic (usually high density polyethylene, HDPE) rings in sizes between 0.6 m and 1.8 m diameter, which are progressively raised with each lift of the waste. These chambers may be placed in sumps at the base of engineered drainage layers, forming part of a larger gravity drained dewatering system. During landfilling, or when the final level of the landfill has been reached, the chamber may be fitted with a steel or plastic liner and the annulus backfilled with gravel. This can extend the operating life of deep chambers, especially those constructed of concrete, which are prone to failure due to differential settlement.

3. **Upslope risers**. These are constructed during the initial engineering of the landfill. Complete pipe-strings are laid against the sloping liner, or along liner batters, to the upper edge of the landfill. The base of the riser may be connected to an engineered basal drainage system, or to peripheral drains. Upslope risers will generally be constructed of plastic pipe, with slotted sections toward the base of the landfill.

4. **Retro-fitted boreholes**. These wells are installed from the landfill or restoration surface through the waste mass. Retro-fitted wells may be installed as part of a well field, often placed in grids, with the well spacing calculated to allow leachate heads to be drawn down to and held at a certain level.

Although the mechanisms and processes discussed may be relevant to all vertical well types, this thesis will focus on retro-fitted vertical wells only. Throughout the remainder of this thesis, the terms ‘leachate well’ or ‘vertical well’ will, therefore, refer only to retro-fitted vertical leachate extraction wells.

2.3 Retro-fitted vertical wells

A retro-fitted well is defined as a hole, shaft or excavation used for the purpose of extracting ground water from the subsurface. These wells are almost always installed vertically into the formation from the surface (exceptions include horizontal wells and inclined drains). The overall objectives of the well design are: to create a structurally stable, long-lasting, efficient well that has enough space to house pumps or other extraction devices; to allow water to move unrestricted and free of sediment from the aquifer into the well at the desired volume and quality; and to prevent bacterial growth and material decay in the well (Harter, 2003).

Although comprehensive guides and standards are available for the design and construction of groundwater wells (for example, Driscoll, 1987, Preene *et al*, 2000), there is very little guidance for the installation of leachate wells in landfill. Some advice as to the design of dewatering systems is offered in Waste Management Paper 26b (Department of the Environment, 1995), and Last *et al.* (2004) make suggestions for the Best Available Practice (BAP) for different leachate collection system designs, but no specific requirements or recommendations as to materials, design and installation technique are given. Because of this, wells may be installed on the basis of cost and the availability of resources, rather than on how the local site conditions will affect well efficiency and longevity – how the well will perform over time and how long it will last.

As no current standard exists, the design and construction of leachate wells and the materials and equipment used in installing them can vary considerably between different sites and even across the same site. The design of the well may be based solely on the experiences of the landfill operator: what has worked in the past is frequently used on other sites, although this may not be the ideal design. As part of an Engineering and Physical Science Research Council (EPSRC) funded research project (Powrie and Beaven, 2003), a review of leachate wells from a number of different landfill sites was undertaken. Data, including the installation method, design and construction details, pumping history and piezometric levels, from 54 vertical wells across 11 different sites were collated. The database has been updated as part of this research to include a further 22 wells, 15 from an additional two sites.

2.3.1 Vertical well data base

The intention of the vertical well data base, was to collate enough information on vertical well design, installation and performance, from a number of landfill operators, to enable a qualitative analysis of leachate well design: is a single well design used in most situations, or do wells differ in design and performance to suit site specific conditions? If variations in design and performance were large, it was hoped that known differences in the hydrogeology and hydraulic properties of the landfill material (e.g. age, waste type, depth), could be used to correlate the results.

To be able to draw conclusions and averages from the data, it was, however, important to be sure that the sample wells were representative of leachate wells in general. The data base, therefore, contained examples of landfill wells from different landfill sites, different landfill operators and from different parts of the UK. In 2005, there were approximately 4000 landfill sites in the UK (Environment Agency, 2006). Of these, 923 were registered active and accepting waste materials (HM Revenue and Customs, 2005). Six of the largest operators (by volume of waste landfilled annually (HM Revenue and Customs, 2005)) were approached for well and landfill data: SITA UK, Cleanaway Ltd. (now Veolia Environmental Services), Shanks Group Plc., Biffa Waste Services, Mercia Waste Ltd. (also Severn Waste Services) and Virridor Waste Management Ltd.

Although a significant amount of information was provided by all six operators, it was rare that detailed or consistent records were available from single well fields, or individual wells. Also, at the operators request, some confidential data could not be published. The leachate well database, therefore, contains wells only from those sites where enough data was made available to enable several example wells to be compared, and where at least some historical data was available (e.g. drilling method, waste type, borehole depth, construction materials).

The location of the landfill sites included in the database are shown in Figure 2.1. The sites are located across the south, middle and far north of England, and fall within a similar climatic zone, with an annual rainfall of between 500 and 800 mm (equivalent to an annual effective rainfall of approximately 300 to 600 mm (from site records)). The 13 landfills included in the database contain predominantly MSW (municipal solid waste). MSW is defined as a waste type that includes predominantly household waste (domestic waste) with sometimes the addition of commercial wastes collected by a municipality within a given area. Wastes are in either solid or semisolid form and generally exclude industrial hazardous wastes (e.g. Environment Agency, 2006). Although waste type entering the landfills may differ, to some extent, between sites, it can be assumed, that all the landfills were inherently similar in that each essentially comprise similar, very large anaerobic masses of decomposing organic materials, and the physical and biological processes occurring are therefore similar (Robinson, 2005).

The data collected is, therefore, considered representative of landfill wells in the UK. From the data collected, a typical landfill vertical well field can be described as a number of deep, retro-fitted boreholes, drilled using a barrel auger, lined with screen and casing of diameter 140 - 200mm. Well screen materials are usually steel (with cut slots), HDPE or MDPE, installed with a granular filter pack. A summary of the data is given in Table 2.1, a schematic of a typical vertical well is shown in Figure 2.2. The vertical wells database is reproduced in full in Appendix A.

Samples	76 wells from 13 sites in the UK	
Ave. waste depth	23.0 m	
Ave. well depth	19.7 m	
Drilling method	60 % rotary barrel auger	30 % CFA
Well screen	66 % steel	34 % Plastic (HDPE, MDPE)
Screen slots	3 x 5 to 10 x 100 mm	3 – 20 % open area
Pack type	5 – 40 mm gravel	
Ave. daily yield	0.15 to 59 m^3/day (average 8.5 m^3/day)	

Table 2.1. Summary of vertical well database

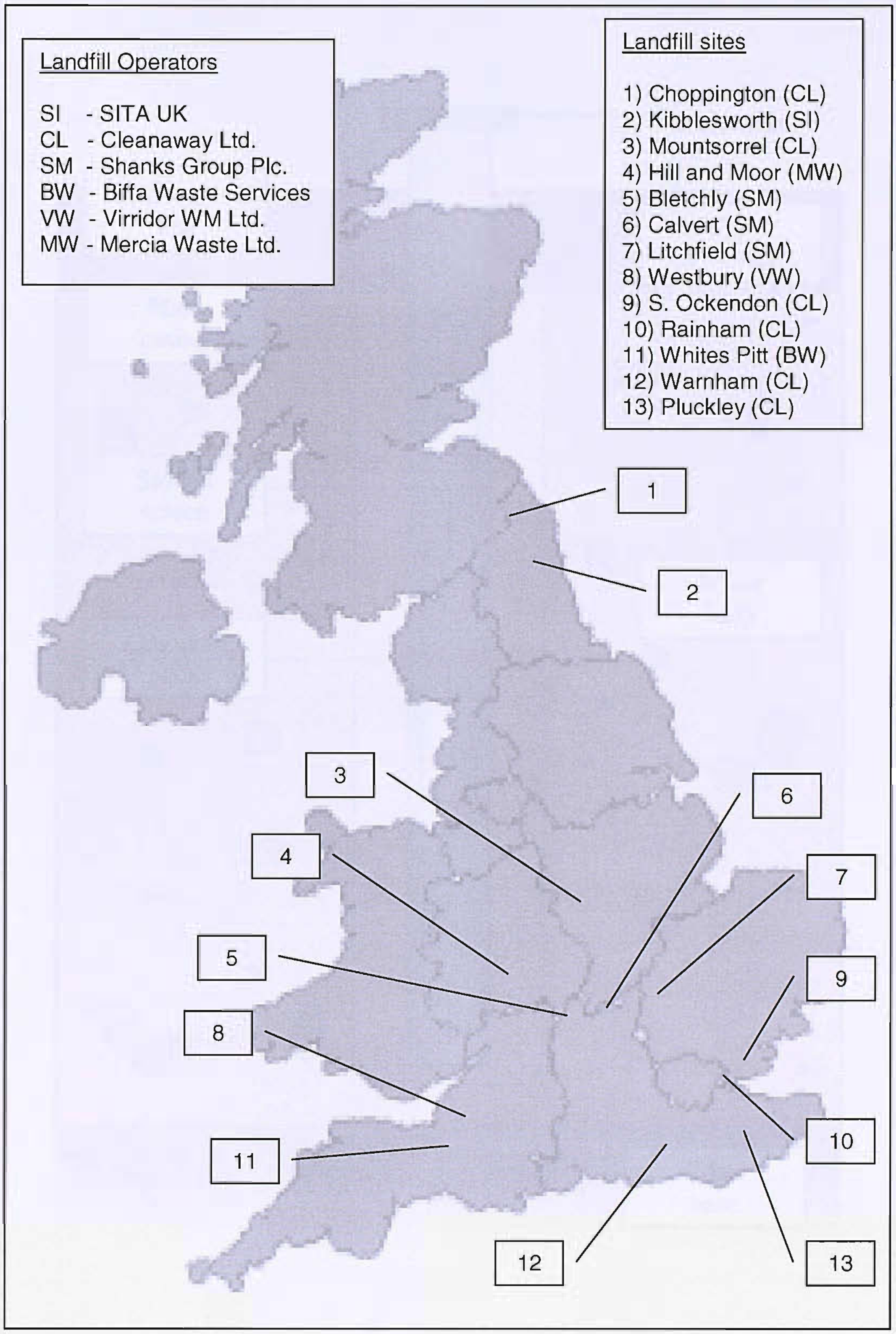

Figure 2.1. Location of landfills used in leachate well data base

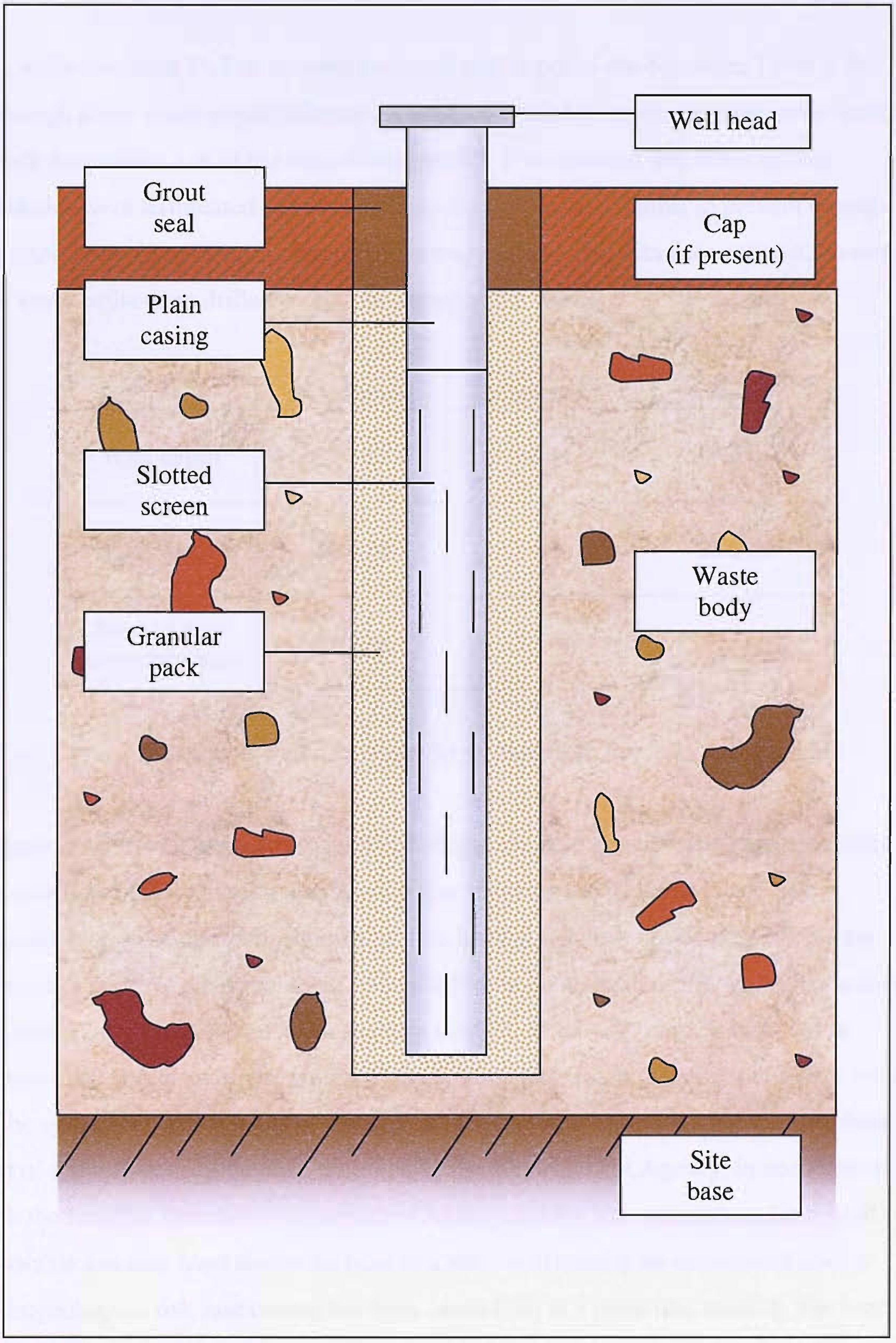

Figure 2.2. Schematic of typical vertical leachate well

2.3.2 Well depth and spacing

The wells averaged 21.7 m in depth (original drill depth of the borehole; Table 2.2). Although some waste depth information was not available, on average the wells were installed to within 3 m of the base of the landfill. It is assumed that when drilled, boreholes were terminated somewhat above the base of the landfill to prevent damage to the underlying formation or a basal dewatering system. The data does suggest, however, that some wells were drilled below the extent of the waste.

	Maximum	**Minimum**	**Average**
Well depth	36.1 m	7.4 m	19.7 m
Waste depth	50.0 m	7.5 m	23.0 m
Base of well above site base	21.8 m	-2.0 m	3.2 m

Table 2.2. Average well and waste depth data from leachate well database

A groundwater well is generally installed deep enough to generate the required yields (or drawdown in dewatering operations) after allowing for well losses and the accommodation of pumping equipment. In a landfill this may not be possible, as the maximum depth of a borehole will be limited to the total depth of the waste. To achieve the maximum possible drawdown across a landfill, wells will often be installed in closely spaced grids with the pumps at the bottom. The combined effect of all the wells in the system should be sufficient to achieve the required drawdown, which may form part of a site license agreement, enforced by the Environment Agency, in accordance with the Landfill Directive (Environment Agency, 2006). The site licence head limit – allowable leachate head above the base of a site - will usually be determined after a hydrogeological risk assessment has been carried out at a particular landfill. The head limit may be set as low as 1 m above the base of the site (Last *et al.*, 2004). If this were the imposed limit for any of the landfills examined in the database, none of the wells included (where leachate head data is given) would enable compliance.

Rowe and Nadarajah (1996), proposed analytical methods for determining the optimum size, number and spacing of leachate wells to obtain and maintain a desired leachate head in a landfill. The authors demonstrate analytically, that the average leachate head (above the base of the landfill) is a function of the radius of the well, the spacing of the well, the percolation rate and the hydraulic conductivity of the waste. In a published example, where horizontal hydraulic conductivity of the waste is 10^{-6} m/sec, percolation is 0.15 m/annum and the well diameter is 1 m, to maintain leachate heads of 1 m, the well spacing should be 20 m (Rowe and Nadarajah, 1996). Although a useful guidance, the hydraulic conductivity of waste can vary significantly with depth, and may vary by several orders of magnitude from point to point (Section 3.4). For deep landfills, this may place a constraint on the control (of leachate heads) that can be achieved for a practical number of wells.

2.3.3 Drilling method

To install a well into a landfill, a borehole must first be drilled from the surface at a size large enough to accommodate the installation. Drilling machinery and equipment designed for hard rock boreholes (rotary drilling) or sediments (percussive drilling) has generally been used to install wells in landfills. More recently, specialised drilling companies with equipment and experience tailored to the heterogeneous characteristics of landfilled waste have become more widespread. Although drilling methods can vary, all must overcome a common problem, that even over a short distance, the type and nature of the landfilled material can vary considerably. As Burrows (1998) states, a single borehole may pass through soft clays, hard rubble, elastic materials, fibrous materials, plastics, paper, impenetrable wood and metal, and loose waste. Of the wells examined in the database, the most common drilling method (used for almost 60 % of those wells where the method is recorded) was rotary barrel auger drilling. Burrows (1998), suggests that this is the only drill tool capable of penetrating or displacing most of these materials. Other drilling techniques include continuous flight auger and shell and auger (Table 2.3).

Drilling Method	**% of known methods**
Cable / percussive	9
Rotary barrel auger	57
Continuous flight auger	32
Other	2

Table 2.3. Common leachate well drilling techniques (from vertical well database)

2.3.4 Casing and well screen design

After a borehole has been drilled, a well screen and casing will be installed (together referred to as the well liner). The well casing is a continuous length of pipe, constructed of connected shorter lengths, that reaches from the landfill surface into the borehole. The well screen is a continuation of the borehole casing, but perforated to allow leachate to flow to the pump, that generally continues to the base of the borehole. The well screen and casing serve two purposes: preventing the borehole from collapsing, and preventing fines from entering the well on pumping.

For use in groundwater wells, the well screen is usually chosen to:

- be resistant to corrosion,
- be strong enough to prevent collapse,
- offer minimal resistance to flow of water,
- prevent the continued movement of particulates into well.

In practice, the choice of well screen may be a compromise of the above.

Table 2.4 summarises casing material data from the well database. Of the wells examined, well screen materials were either steel or plastics such as HDPE, with steel being the most common. Other well screen materials available for use in landfill include stainless-steel, PVC and other plastics.

Material	%
HDPE	23
MDPE	11
Steel	66

Table 2.4. Common landfill well screen materials (from vertical well database)

To allow free movement of leachate into the well, the well screen will be perforated either with slots or holes. Slots can be die-punched, torch-cut (steel well screens), saw-cut (plastic well screens), bridged or formed by wire-wrapping. Holes may be drilled, punched or torch-cut. Of the wells studied, steel well screen perforations were predominantly torch-cut and plastic well screens saw-cut, either horizontally or vertically.

The number and dimension of the slots around a well screen will determine the total open area. If the well screen has a large open area, the entrance velocity of leachate into the well will be low and head loss at the screen minimal. However, as the open area increases, the well screen will become structurally weaker. In deep landfills that can experience significant and rapid settlement and movement both vertically and laterally (for example, on the sloped flanks of a land-raise landfill), the strength of the well screen may override the choice of screen material and open area. Investigations by Clark and Turner (1983), suggest that, hydraulically, there is no merit in having a screen open area above about 10 percent).

Of the wells examined in the database, steel well screen with torch cut slots generally had slot openings of dimensions 10 mm × 100 mm, with an open area of 3 - 4 %. Slot sizes in plastic well screens ranged between 3 mm × 170 mm and 3 mm × 5 mm, with an open area of up to 20 %.

The maximum slot size of the well screen will also be influenced by the size of the filter pack used. When installing groundwater wells, it is recommended (e.g. Driscoll, 1987) that the chosen slot size should retain the D_{90} of the filter pack media (where the D_{90} is the maximum aperture though which 90 % of a soil sample will pass in a particle size distribution analysis). Larger slots may result in the filter pack being washed into the well bore, whereas smaller slots may unnecessarily restrict the flow of groundwater to the well. If this sizing recommendation had been followed in the design of the wells examined in the database, then, assuming the gravels were fairly uniformly graded, slots are generally well-sized for the filter packs used. For example, almost 25 % of the wells were installed with a 20 mm filter pack and a well screen with 10 x 100 mm slots. Although particle size distribution (PSD) curves are not available for these gravels, the D_{10} of a typical 20 mm single sized gravel is between 7.8 and 10.3 mm (e.g. Cardigan Sand and Gravels, 2004; Bardon Aggregates, 2003). The recommended slot size would therefore be around 8 mm, although Driscoll (1987) suggests that a +/- 8 percent tolerance is sufficient.

2.3.5 Filter pack

A filter pack will usually be installed in the annulus between the well screen and borehole wall. The filter pack serves a number of purposes: to support the annulus around the well screen preventing the formation from collapsing onto the well screen, increasing the effective hydraulic diameter of the well and to prevent material being carried in from the surrounding formation into the well. Filter packs will be discussed further in Section 3.7.

Details of the filter pack grain size of wells in the database are given in Table 2.5.

Filter Pack Size (mm)	%
5	13
10	4
20	43
40	11
Unknown	29

Table 2.5. Filter pack grain sizes from data collated in the vertical well database

2.4 Landfill Well Performance

Landfill operators often report disappointing or inconsistent yields (volume of leachate removed from the well over time) from both new and old wells installed in landfill, yet there has been no published research of leachate well performance since Giardi (1997), Burrows *et al.* (1997) and Friend and Hock (1998). In the well database, leachate yields ranged from 0.1 m^3/day to over 50 m^3/day (average 11 m^3/day). Although variations in yields may be expected when comparing the performance of leachate wells from different landfills (because site conditions may vary by waste type and depth of installation, saturated depth etc.), large differences in yields also appear to be common between wells installed in close proximity at the same landfill. Example of well performance data from two landfill sites are presented and discussed below.

2.4.1 Litchfield landfill

Well No.	Bore Hole Depth (m)	Max. Yield (m^3/day)	Ave. Yield (m^3/day)
DB19	23.60	23.68	10.18
UE7	27.00	15.67	4.81
UH2	16.00	29.78	8.32
UH12	18.50	2.54	0.63

Table 2.6. Well performance data from the Litchfield landfill, Bedfordshire

Table 2.6 presents data from the Litchfield landfill, Bedfordshire. The four wells were drilled in a similar waste type (MSW with some hazardous liquids) and installed within a short time frame (between September 1996 and February 1997). Each well was fitted with a pneumatic displacement pump. The average daily yields from each of the wells range from 0.63 m^3/day to 10.18 m^3/day. The most significant difference between the four wells in terms of design and installation is the depth of the boreholes: there is an 11 m difference in depth between wells UE7 and UH2. The depth of the wells, however, does not appear to have a noticeable influence on performance. The deepest of the four wells, well UE7, for example, has a daily yield of 4.81 m^3/day, almost half that of the shallowest well, UH2 (8.32 m^3/day). The daily yield from well DB19 (10.18 m^3/day), however, is more than double that of well UE7, even though they are drilled to approximately the same depth.

Other wells installed at the Litchfield landfill of a similar depth, but of an older age (installed in 1994), show a similar inconsistency in yield when pumped. Well GD9, for example, is reported to have had a maximum flow rate of 4.3 m^3/day. The yield from well A1-4 is an order of magnitude higher at 50.4 m^3/day.

The wide range of daily pump yield is most clearly seen when comparing well yields from a group of wells in a single well field. Figure 2.3, shows the distribution of daily well yield data from 71 wells in the Phase 1 area of the Litchfield landfill (the full well field is not included in the data-base as only limited site records exist for the majority of the wells). Yields range from 0.4 to 15.1 m^3/day. The histogram can be described as having a log-normal distribution of daily flow rates, which may due to spatial variations of the hydraulic conductivity of the waste (see Section 3.2.4).

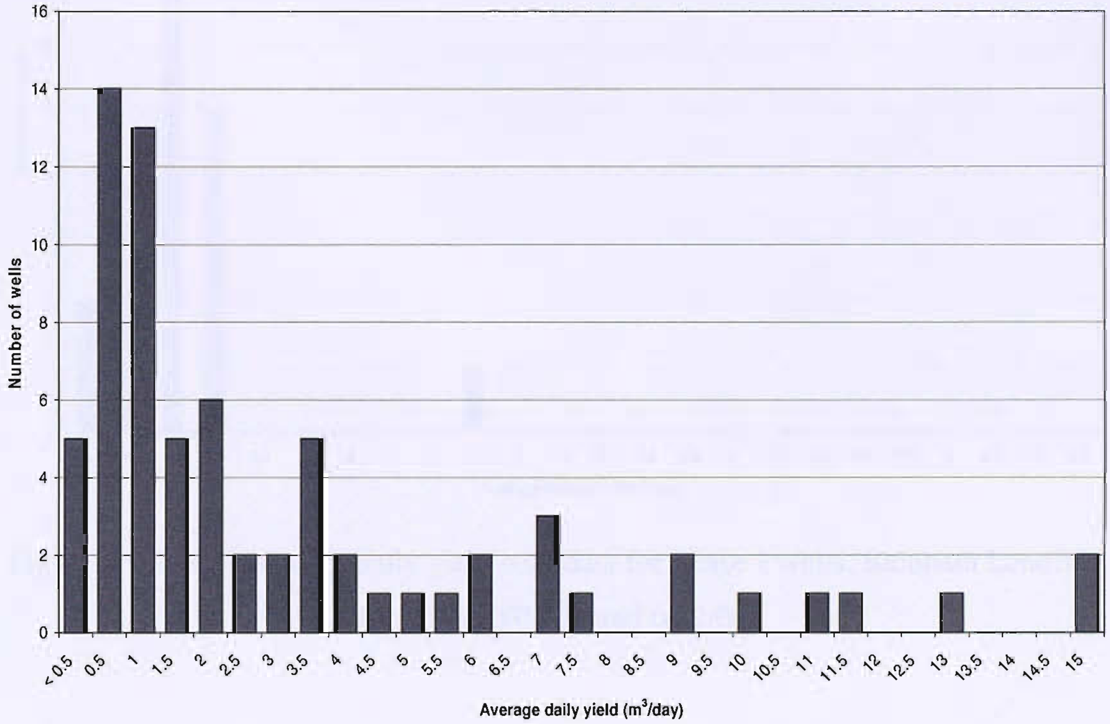

Figure 2.3. Distribution of daily yield well data for Phase 1 wells, Litchfield Landfill, between 4/03/97 and 4/03/99

2.4.2 Rainham Landfill

A similar distribution pattern is also evident in well yield data from two phases of the Rainham landfill in Essex, Figures 2.4 and 2.5. The waste type in each phase is MSW with some fine silts from river dredging works deposited below the waste. Landfilling began in Phase 1 in 1984, and in Phase 2 between 1984 and 1992. The two phases are separated in the landfill by engineered bunds. There is no hydraulic connection between the two phases. All wells in each phase were drilled using rotary barrel auger techniques, installed with 178 to 190 mm steel well screen with torch-cut slots and a coarse (20 to 40 mm) gravel pack. Average daily yields range from 0.13 to 0.72 m^3/day Phase 1 and 0.24 to 4.50 m^3/day in Phase 2.

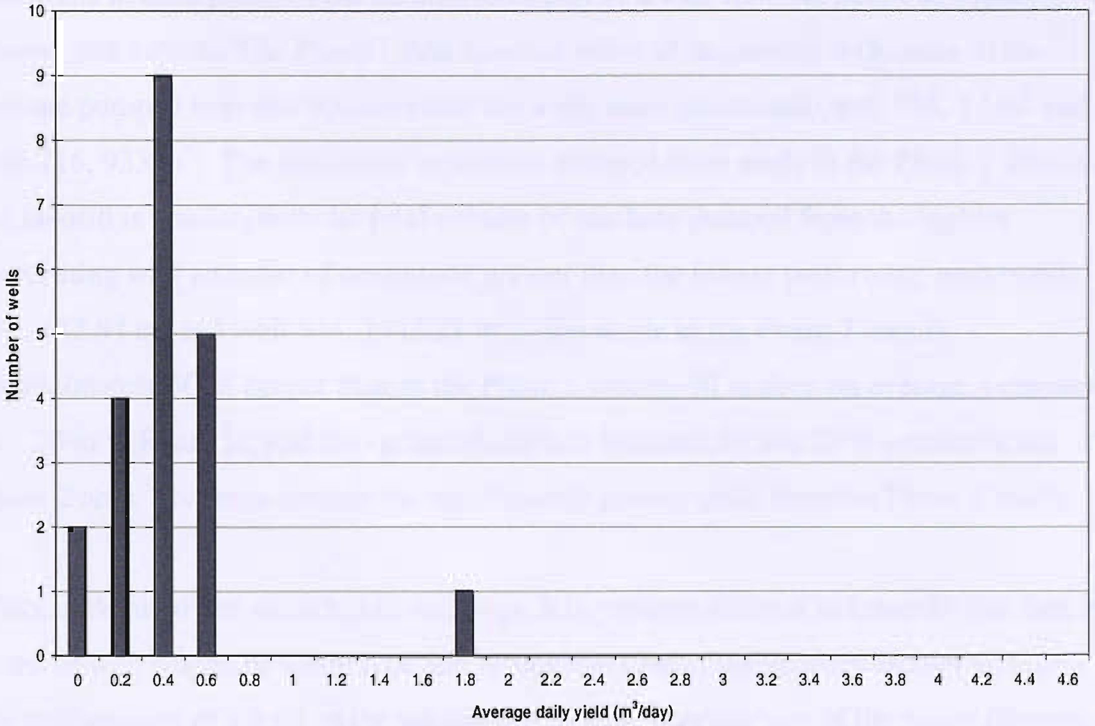

Figure 2.4. Distribution of daily yield well data for Phase 1 wells, Rainham Landfill, between 10/05/00 and 6/12/01

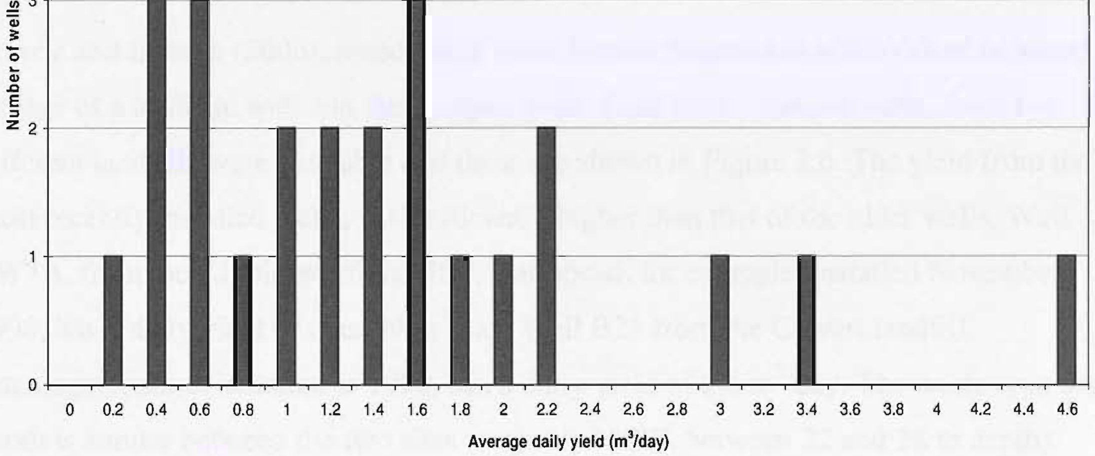

Figure 2.5. Distribution of daily yield well data for Phase 2 wells, Rainham Landfill, Essex, between 22/6/00 and 9/7/01

The wells in each phase of the landfill form part of a well field set out in an evenly spaced grid pattern. The Phase 1 data show an order of magnitude difference in the volume pumped over the 400 days that the wells were monitored (well 736, 57 m^3 and well 716, 933 m^3). The difference in volume pumped from wells in the Phase 2 area of the landfill is similar, with the total volume of leachate pumped from the highest performing well an order of magnitude greater than the lowest performing well (well 376, 182.84 m^3 and well 344, 1945.21 m^3). The waste in the Phase 2 area is approximately 50 % deeper than in the Phase 1 area (~ 30 m deep on average, compared to ~ 20 m in Phase 1), and the saturated depth is between 50 and 75 % greater in the Phase 2 area. This may explain the significantly greater yield from the Phase 2 wells.

Without detailed site records and well logs, it is perhaps difficult to quantify this data is terms of well design or waste type and saturation. One of the primary factors affecting the performance of a well, is the saturated hydraulic conductivity of the waste (Beaven and Powrie,1995, Hudson *et al.*, 2004). The probability distribution of well yields shown in Figure 2.3 to 2.5, is similar to that often found in fine soils (Freeze, 1975, Baker and Bouma, 1976), and is usually attributed to natural variations in soil composition, water content and compaction. The differences in pumped leachate well yields, may, therefore, be due to spatial variations in waste hydraulic properties. This will be discussed further in Section 3.3.

2.4.3 Falling yields with time

Powrie and Beaven (2003), noted that a weak inverse correlation was evident between the age of a leachate well and the pumped yield. Data from nineteen wells, from five different landfills were available and these are shown in Figure 2.6. The yield from the most recently installed wells, is significantly higher than that of the older wells. Well LW7A, from the Kibblesworth landfill, Gateshead, for example, installed November 1998, has a daily yield of over 59 m^3/day. Well B21 from the Calvert landfill, Buckinghamshire, installed in 1990, has a daily yield of 2.4 m^3/day. The waste type and depth is similar between the two sites (majority MSW, between 22 and 28 m depth). Both wells were installed with 200 mm HDPE well screen with a granular filter pack.

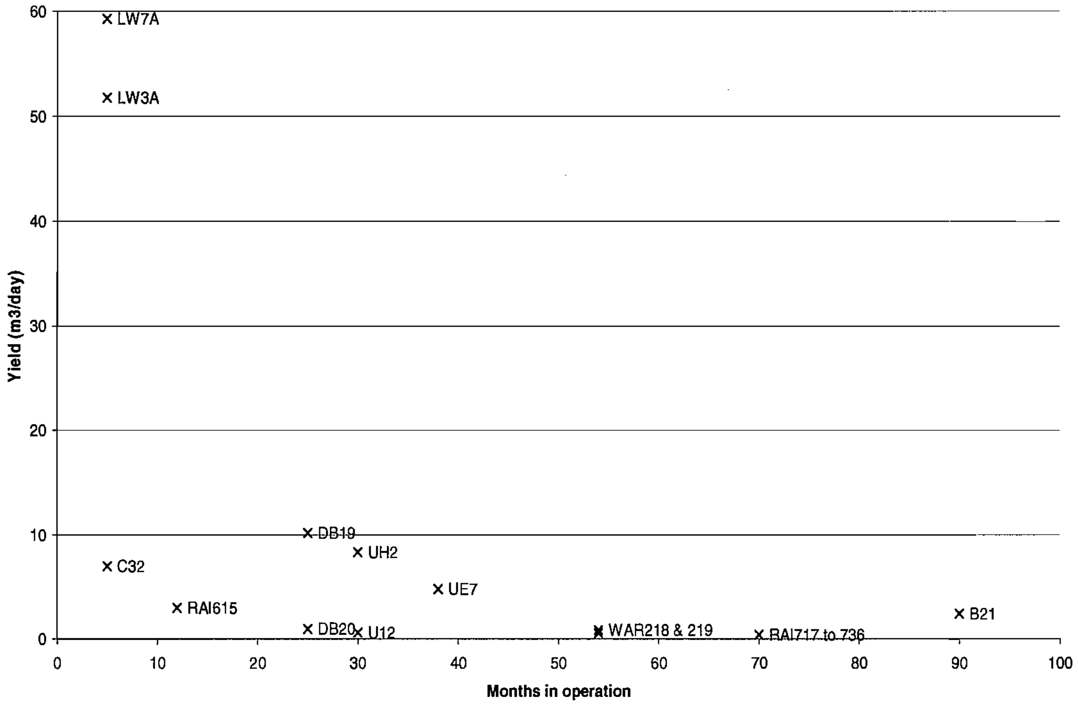

Figure 2.6. Yield vs age for wells examined in the vertical wells database

The deterioration in the performance over time of individual wells installed within the same well field is also commonly stated by landfill operators. Data from the Phase 2 area well field of the Rainham landfill, demonstrates how the long-term performance of individual wells installed to the same design and age in the same waste type can vary (Figure 2.5). Yields from individual wells were monitored for a period of over 400 days. Of the 25 wells examined, 72 percent showed a decrease in performance with yields falling by an average of 57 % during the monitoring period. Data from 10 non-pumped observation wells show that no or very limited dewatering of the waste had taken place during the monitoring period.

Differences in well performance between different landfills may be expected. The waste type, age and depth, the degree of dewatering, infiltration can vary significantly. However, as demonstrated in Figures 2.3 to 2.5, comparing the performance of individual wells may be complicated due to the distribution of hydraulic properties spatially and with depth. Some caution is therefore required when comparing well data. For example, in Figure 2.6, a good new well may be being compared to a bad old well.

It is not possible to conclude from the data available whether wells are genuinely underperforming, or simply dewatering the landfill locally around individual wells. Over time, wells may begin to clog, with microbial and chemical deposits, or due to siltation in the well bore and filter pack. As the waste is loaded (through burial), it will compact, reducing flow paths to the wells lowering the hydraulic conductivity. These, and other possible reasons for well performance deterioration will be examined in Chapter 3.

2.5 Chapter Summary

The research conducted by Powrie & Beaven (2003) and the information gathered in the leachate well database, suggests that although some variation does exist in leachate well design, with construction materials and installation methods varying both between sites and within the same site, many leachate wells are installed using similar techniques and materials: rotary barrel auger drilling, installed with a steel well screen with torch-cut slots, with a coarse gravel pack. Where variations in design do exist, for example, with different screen types, pack sizes etc., these do not appear to be attributable to the local waste characteristics and may not always be due to site specific design needs.

Making comparisons between wells installed in waste and those installed for abstraction purposes in natural formations is difficult. Waste may be extremely heterogeneous, with physical properties that may change over time due to degradation and compaction, in contrast to more static natural formations. Basic rules for selecting well screens and filter packs, which may be relevant to some leachate wells, appear not to have been used for all well installations.

Performance data collected in the database and data from the Litchfield and Rainham Landfills, show how yields can vary significantly between individual wells installed in an apparently identical manner and to the same specification. The wells examined also tended to show a weak inverse correlation between the age of a well and the pumped yield. Lack of complete information, however, makes comparisons of performance data between wells of different landfills more difficult. Detailed pumping history, leachate levels and complete construction details appear to be rare in landfill records.

Chapter 3

Factors known to affect well performance

3.1 Introduction to chapter

The review of leachate wells in the previous chapter has shown how the performance of wells can vary considerably between wells installed to the same design, in the same landfill, and that over time, the performance of wells may decline. Reasons for this apparent ineffectiveness and deterioration are suggested by Powrie and Beaven (2003). These can be broadly categorised as either well related or waste related:

Well related

- design and structural integrity of the well screen and pack,
- disturbance of the formation during drilling of the well leading to clogging,
- clogging of the filter pack by particles of wastes, microbial growth and inorganic precipitates,
- the entry of sediment into the well, reducing the depth at which pumps can be installed,
- the operation of the well including type of pump, depth of drawdown and the long term reduction in saturated depth,
- development strategy.

Waste related

- reduction and variations in waste hydraulic conductivity with depth, and over time,
- increasing effective stress in waste surrounding the well either as a result of ongoing landfilling and increased overburden pressures, or as leachate is extracted and porewater pressures reduce, both resulting in reduced permeability,
- dewatering and reduction in saturated depth over time,
- the characteristics of the local leachate (viscosity and temperature),
- the effects of gas in the saturated zone, restricting flow paths through the waste.

Well related factors can be considered as being 'well specific' and may affect only individual boreholes and specific well designs, such as the drilling method and the type of screen and filter pack used, and may in part account for the differences in performance often evident between wells installed on the same site. Waste related factors, such as hydraulic conductivity and the compaction of waste over time will affect, to some degree, all wells installed within the same site and may be responsible for the general decline in performance of landfill wells over time. Due to the heterogeneous nature of waste, there will always be some cross-site variations, and both well and waste related factors may be inherently linked. The extent of smearing, for example, around the walls of a borehole, will be governed by both the drilling technique used and the local waste type and daily cover soils drilled through.

It is useful, nevertheless, to differentiate between waste and well related performance factors, as an understanding of each can help in the design, installation and maintenance of new wells. In the groundwater industry, established techniques are followed to help maximise the efficiency of a well. For example, there are rules (e.g. Preene *et al.*, 2000) for selecting filter pack grades and well screens for maximum yield from the formation and to reduce the likelihood of clogging and fouling over time. The correct choice of filter pack will both extend the effective diameter of the well and help prevent fines mobilising into the well and clogging the well screen and well bore. If groundwater wells do begin to clog with sediments and from microbial deposits, techniques are available to develop and remediate the well, which may also be applicable to landfill wells.

In this chapter, the possible causes of well ineffectiveness and deterioration will be discussed. Well hydraulics and how the design of a well can affect performance will be examined. Current knowledge of waste hydraulics will be reviewed to determine to what extent waste compaction and degradation will affect well yields over time. The processes of biodegradation and leachate generation will be examined, as these determine the rate and extent of biological clogging mechanisms and compaction within a landfill body. The mechanisms of microbial and physical clogging and how these could affect the performance of a vertical well will be discussed. Finally, the methods used in the groundwater industry to develop new wells and remediate failing wells will be discussed in the context of applying the techniques to landfills.

3.2 Hydraulic conductivity and waste hydraulics

The efficiency of a well is directly and critically dependent on the hydraulic conductivity (k) of the immediately adjacent material (Barrows *et al.*, 2001). Hydraulic conductivity is defined as the capacity of a porous medium to transmit water (Nielsen, 1991). The hydraulic conductivity of a material will be governed by the size and shape of its pores, the effectiveness of the interconnection between pores, and the physical properties of the fluid passing through them (Driscoll, 1987). If the interconnecting conduits are small the volume of liquid passing from pore to pore is restricted and the resulting hydraulic conductivity is low. In a reasonably coarse grained material, the connecting conduits are large relative to the size of the pores and the hydraulic conductivity will be high. In landfill, quantifying the flow of liquid between pores is complicated because waste may be extremely heterogenic across a given site. In a unit volume of waste, individual grain sizes and material type can vary significantly.

In a landfill, the saturated portion of the waste may be regarded as an aquifer. Because of heterogeneity, even over a short distance, aquifer losses (the difference between the static water level in the aquifer and the water level observed in the aquifer immediately adjacent to the well casing or screen during pumping) in flows toward individual wells may also vary significantly. The aquifer loss component of drawdown can also be expected to change over time, as the hydraulic properties of the waste change. The age of the waste, degree of degradation and compaction, the waste type and processing etc. may all affect the flow of leachate toward the well.

Investigations have been carried out to determine the hydraulic properties of waste. These have included the pumping of actual landfill wells (e.g. Giardi, 1997, Burrows *et al.* 1997) and tests carried out in large scale laboratory apparatus (e.g. Beaven and Powrie (1995 and 1999), Hudson *et al.*, (2004)). A range of hydraulic conductivities for waste have been reported, between 1×10^{-4} and 4×10^{-9} m/sec. Some published data is given in Table 3.1.

Investigation	**Waste characteristics**	**Hydraulic conductivity (m/sec)**
Knox (1991)	MSW	1×10^{-4} to 1×10^{-7}
Beaven (1996)	Loosely compacted MSW	1×10^{-4}
	Surcharged MSW	8×10^{-6}
Cusso *et al.* (1997)	MSW	1×10^{-5} to 1×10^{-6}
Burrows *et al.* (1997)	Sites with daily cover	2×10^{-5} to 4×10^{-7}
	Site with no daily cover	7×10^{-5} to 2×10^{-5}
Powrie *et al.* (1999)	MSW	3×10^{-5} to 1×10^{-7}
	Processed MSW	2×10^{-4} to 4×10^{-9}

Table 3.1. Range of published waste hydraulic conductivity

When waste is loaded by overlying material, the solid waste matrix is compressed, a quantity of leachate is released from storage and the drainable porosity and hydraulic conductivity decreases. Beaven and Powrie (1995) and Hudson *et al.*, (2004) describe a series of large-scale compression tests carried out to investigate the properties of landfilled waste under increasing vertical stress. The waste types investigated included processed and unprocessed MSW, pulverised MSW and aged MSW. The tests were carried out in a two-metre diameter, three-metre high cylinder that was filled with wastes and loaded with a piston to simulate depths of burial from 0 to 60 m. After the wastes had stabilised, generally within two to seven days, the wastes were saturated with water and allowed to drain under the influence of gravity to field capacity. The parameters measured during the process included bulk density, mechanical compressibility, absorptive capacity, field capacity, effective porosity and hydraulic conductivity.

From these tests, Table 3.2 shows the reported values for the saturated hydraulic conductivity of MSW as a function of applied stress (Powrie and Beaven, 1999). The hydraulic conductivity is seen to decrease by almost four orders of magnitude, from 1.5 $\times 10^{-4}$ to 3.7 $\times 10^{-8}$ m/sec, as the applied stress increases from 0 to 600 kPa.

Applied Stress (kPa)	**Average vertical stress (kPa)**	**Hydraulic conductivity (m/s)**
40	34.1	1.5×10^{-4} to 3.4×10^{-5}
87	64.9	8.2×10^{-5} to 1.9×10^{-5}
165	120	2.8×10^{-5} to 3.1×10^{-6}
322	241	8.9×10^{-6} to 4.4×10^{-7}
600	463	2.7×10^{-7} to 3.7×10^{-8}

Table 3.2. Variation in saturated hydraulic conductivity with vertical stress for MSW (from Powrie and Beaven, 1995)

The hydraulic conductivity of MSW will also be controlled by waste composition, age and intermediate (daily) covers that may have been constructed between lifts within the waste (Figure 3.1). Aged or degraded wastes might be expected to have a lower hydraulic conductivity than when fresh, owing to the effects of particle size reduction and an increased bulk density, though stress through loading will have the biggest effect (Powrie and Beaven, 1995). Low permeability materials (for example, reworked clays) are often deliberately used as daily cover soils to minimise, amongst other things, odour emissions and infiltration (Vesilind, 2001). This material may have a significantly lower hydraulic conductivity than the waste itself, resulting in alternating horizons of changing permeability. From field tests and excavations, Burrows (1998), concludes that up to 29 % of a landfill's post-settlement fill depth can constitute daily and intermediate cover material. Other daily cover materials include sand, chemical foams, tire chips and geotextile covers (Daniel, 1993), though owing to the costs and local availability of resources, soils are the more common.

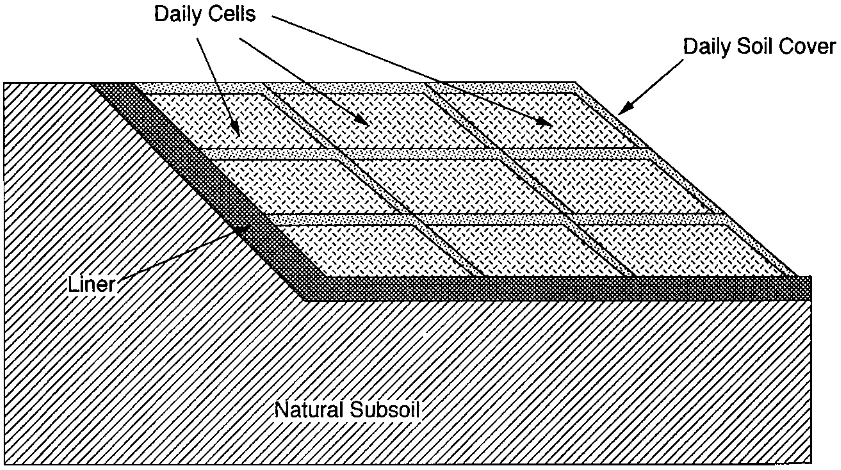

Figure 3.1. Daily cells in a landfill (reproduced from Daniel, 1993)

3.2.1 Density and viscosity of leachate

Hydraulic conductivity is also dependent on both the intrinsic permeability of the media and the physical properties (fluid viscosity and density) of the permeant (Freeze and Cherry, 1979). The density and viscosity of the permeant are functions of temperature and the composition of a particular leachate (Watkins, 1997). The viscosity of water changes by about 3 % for every 1°C change in temperature (Daniel, 1993), and leachate viscosity can also be expected to change with increasing or decreasing temperature (though there is currently no published range). Temperatures within a landfill can be high, and will change over time due to the degradation process (Section 3.5.1). Temperatures of between 20 and 80 °C are common (Barlaz and Ham, 1993). During the drilling and installation of boreholes at four different landfill sites in southern England, Burrows *et al.* (1997), measured leachate temperatures between 18 °C to 64 °C. Some differences can, therefore, be expected between hydraulic conductivity values calculated in laboratory apparatus at standard or ambient air temperature, and those within a landfill site.

The density and viscosity of landfill leachate will also be controlled by leachate quality. The viscosity of leachate can be 1 to 15 % higher than water at the same temperature (Watkins and Elliot, 1997), and the density of leachate, with a typical dissolved solids concentrations of 20,000 mg/l, will be about 1% higher than that of water (e.g. Poulsen *et al.*, 2000).

3.2.2 Effective stress and landfill gas

A reduction in waste hydraulic conductivity near the well may also be expected due to increased effective stress. The total stress acting on the waste at a given point is the weight of the overburden. In saturated materials, this stress is partly supported by the solid waste matrix and partly by the pore water pressure of leachate within the waste. When leachate is removed by pumping from a vertical well, the pore water pressure drops, the proportion of the load carried by the solid waste matrix increases, the matrix is further compressed and the hydraulic conductivity decreases. The drop in pore water pressure, and therefore the degree of compression, will be greatest immediately adjacent to the well.

A further reduction in drainable porosity and hydraulic conductivity can occur due to the accumulation of gas within the waste (Hudson *et al.* 2001). This may occur in all parts of the landfill, though especially where gas is confined by overlying relatively impermeable waste. Gas bubbles will reduce the hydraulic conductivity of waste by blocking flow paths through the waste and decreasing the size of the water conducting pores. In column tests to monitor the microbial clogging of 6 mm aggregates, Nikolova (2004) reported an 8 percent reduction in drainable porosity as a result of the formation of gas bubbles on the aggregate surface. Nikolova (2004), concluded that gas bubbles accumulated mainly in the top column sections where microbial activity was most pronounced and consequently the gas production most vigorous. The production of gas will also depend on the pore water pressure within the waste. A higher pore water pressure would result in an increased solubility of the gases in the leachate and consequently less accumulation of bubbles. When the waste is dewatered, for example through pumping from a vertical well, the pore water pressures in the zone of influence around the well decrease and gas will be released.

3.2.3 Dewatering and saturated depth

If a greater volume of liquid is removed through pumping than is replenished through infiltration, the volume of free-draining liquid in the waste - and therefore the saturated depth - will decrease. As the saturated depth decreases, the hydraulic head driving flow to a pumped well will also decrease. Over time, as leachate is removed, yields from pumping wells may be expected to fall. In deep landfills where loading has reduced the hydraulic conductivity of the waste, the fall in yield as the waste dewaters may be disproportional to the reduction in saturated depth.

The performance of the well will, therefore, be a function of both the saturated depth, and the depth of the well. A deep 30 m well, with a 10 m saturated depth, for example, will be less efficient than a shallow 12 m well with a 10 m saturated depth, owing to reduced hydraulic conductivity with depth (Figure 3.2). From Table 2.1, the average borehole depth was 22 m, with a range of 7 to 36 m. The saturated depth ranged from 3.5 to 21.9 m. Figure 3.3 compares the saturated depth/waste depth (H_{sat}/H_{waste}) with average daily yield for wells in the database discussed in Chapter 2. Yield could be expected to increase with increasing H_{sat}/H_{waste}, as shallow wells with a large H_{sat} would produce more leachate. This is not evident in Figure 3.3, which would suggest that hydraulic conductivity and saturated depth are not the only controlling factors for these wells.

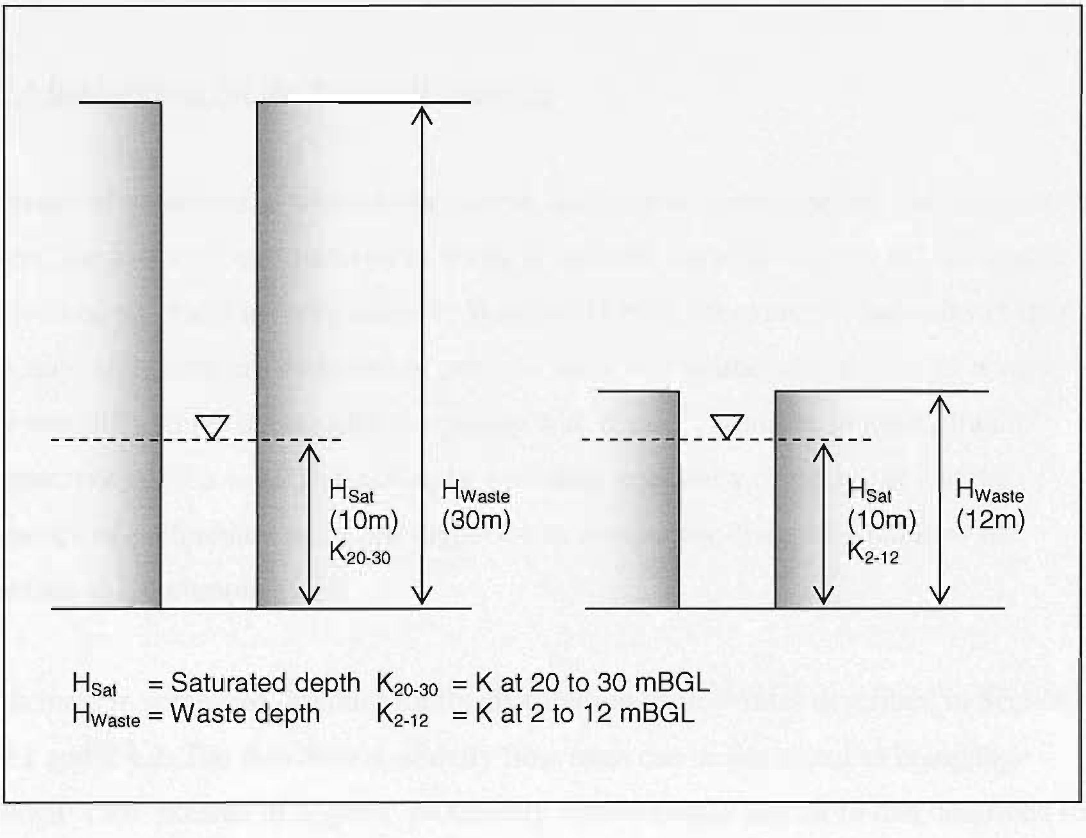

Figure 3.2. Saturated depth and hydraulic conductivity (K) at different waste depths

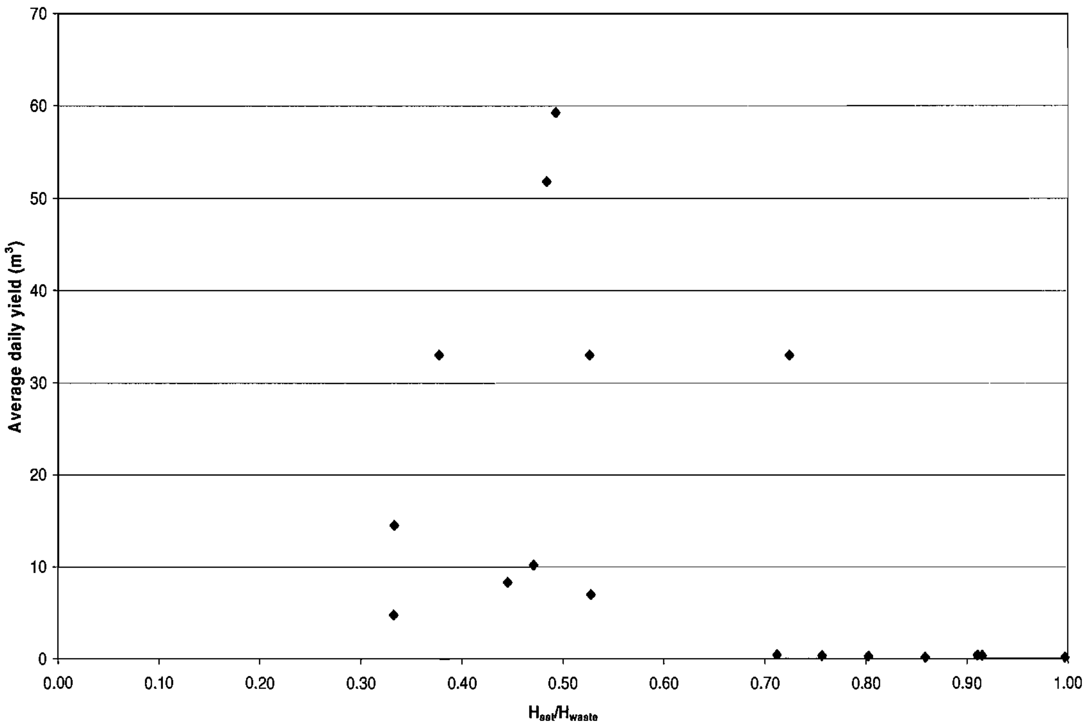

Figure 3.3. Daily flow rates vs saturated depth / waste depth (H_{sat}/H_{waste}) from vertical well database

3.2.4 Implications for leachate well pumping

Because of variations in waste composition, daily cover, water content and compactive effort, the hydraulic conductivity of waste is spatially variable and can not be specified with certainty. Field investigations by Burrows (1998), for example, have shown that the zone of dewatering surrounding pumped wells was neither circular (in plan view) nor smoothly and exponentially steepening with depth. Variations in the hydraulic conductivity of the waste, breaks in the hydraulic continuity of the waste and the presence of preferential paths are suggested as reasons for disrupting the flow of leachate to the pumping well.

This may, in some part, account for the distribution of flow rates described in Section 2.4.1 and 2.4.2. The distribution of daily flow rates can be described as being log-normal. This 'skewed histogram' probability distribution is similar to that described for hydraulic conductivities in fine-grained soils (e.g. Stedinger, 1980, Zhai & Benson, 2006), and is usually attributed to natural variations in soil composition, water content and compaction (Freeze, 1975, Baker and Bouma, 1976, Hoeksema and Kitanidis, 1985). The distribution of flow rates described in Figures 2.2. to 2.4, may in part be due to variations in the hydraulic properties of the landfill. Analysis of the well data including yield and saturated depth does, however, suggest that the range in performance is not just a function of hydraulic conductivity, but that a combination of controlling factors are involved, including microbial and physical clogging of the well screen.

3.3 Microbial clogging of the filter pack and well screen

The biodegradation of organic waste will result in heavy nutrient loading in typical landfill leachate (Qasim and Chiang, 1995). Over time, an accumulation of microbial deposits in the filter pack and well screen of a vertical leachate well and other drainage media can occur. This microbial clogging, or biofouling, may affect all aspects of a well, with biofilms and microbial encrustations forming in the gravel pack, well screen and the area of waste in closest contact with the gravel. Microbial activity may include various forms of slime formation and biologically-induced precipitation of minerals to form encrustations (Bass, 1985). The accumulation of mineral clog deposits, biodegradation products and biofilms may eventually result in the partial or total occlusion of the void space of the filter pack material, lowering its permeability, and over time, a significant reduction in well performance, as the filter pack becomes clogged, could be expected.

The extent and rate of microbial clogging around a leachate well will be dependant on the pore space in the filter pack, the thickness of the filter layer, the face velocity, the leachate temperature, and the nutrient status of the leachate (Wang and Banks, 2006).

3.3.1 Biodegradation and the production of leachate

When waste is deposited, biochemical reactions will take place as a result of the presence of the reactive, organic material. In untreated waste, this may account for more than 40 percent (by dry weight) of the waste (Barry *et al.*, 2001). As water percolates downwards through the landfill, organic and inorganic material will be leached from the waste and leachate will be produced. The properties of the leachate will be determined by the composition and solubility of the waste components. As the waste changes in composition due to biodegradation, the leachate quality and biological loading will also change with time.

Biodegradation will begin as soon as waste is deposited. Five reaction stages can be identified (e.g. McBean *et al.*, 1994) :

Stage 1: Hydrolysis & aerobic degradation

The initial stage of organic decomposition occurs when waste is first deposited in the landfill and for the period of time for which oxygen is available within the waste. Chemical processes are initiated and facilitated by the presence of aerobic bacteria which metabolise a fraction of the organic waste to produce simpler hydrocarbons, water, carbon dioxide and heat. Some of the carbon dioxide will dissolve in the water, forming a leachate that is rich in carbonic acid, lowering the pH. This initial stage in decomposition can last from a number of days to several weeks, depending on the amount of oxygen that is available within the waste. This will be controlled by site operations, which influence depth of waste deposition, waste type and degree of mechanical compaction (Barlaz and Ham, 1993). The heat produced during aerobic decomposition can sometimes cause the temperature to rise as high as 80 °C – 90 °C.

Stage 2: Hydrolysis and fermentation

The removal of oxygen in Stage 1 facilitates a change in conditions from aerobic to anaerobic, and bacteria within the waste will be replaced by anaerobic species. Carbohydrates are hydrolysed to sugars, which are then further decomposed to form carbon dioxide, hydrogen, ammonia and organic acids. Proteins decompose to form ammonia, carboxylic acids and carbon dioxide. The leachate that is produced at this stage contains ammoniacal nitrogen in high concentration. Acetic acid is the main organic acid formed but propionic, butyric, lactic and formic acids and acid derivative products are also produced, and their formation is affected by the composition of the initial waste material. The temperatures in the landfill will decrease to between 30°C and 50°C. Gas composition may rise to levels of up to 80 percent carbon dioxide and 20 percent hydrogen (Barlaz and Ham, 1993; Nikolova, 2004).

Stage 3: Acetogenesis

In this stage, anaerobic conditions are still present and the organic acids that were formed in the hydrolysis and fermentation stage are now converted to acetic acid, acetic acid derivatives, carbon dioxide and hydrogen. Other microorganisms convert carbohydrates directly to acetic acid in the presence of carbon dioxide and nitrogen. Hydrogen and carbon dioxide levels begin to diminish towards the end of this stage, with the lower hydrogen concentrations promoting the methane-generating microorganisms (methanogens), which subsequently generate methane and carbon dioxide from the organic acids and their derivatives generated in the earlier stages (Barlaz and Ham, 1993). Leachate generated during this degradation stage will contain high concentrations of soluble degradable organic compounds and an acidic pH. Ammonia and metal concentrations will also rise.

Stage 4: Methanogenesis

This stage encompasses the main processes that lead to the production of landfill gas. The chemical processes involved are comparatively slow and can take many years to complete. Oxygen-depleted, anaerobic conditions still remain. Low levels of hydrogen are required to promote the methanogenic organisms, which generate carbon dioxide and methane from the organic acids and their derivatives such as acetates and formates formed in the earlier stages. Methane generation may also occur from the direct conversion of hydrogen and carbon dioxide (via microorganisms) into methane and water. Hydrogen concentrations produced during Stages 2 and 3 will therefore fall to low levels during this fourth stage (Vesilind *et al.*, 2001; Barlaz and Ham, 1993). With the onset of methanogenic conditions, the pH of the leachate will become more neutral or even slightly alkaline (Hester and Harrison, 1995).

Stage 5: Oxidation

Oxidation processes mark the final stage of the reactions involved in the biodegradation of waste. As the acids are used up in the production of landfill gas (as seen in Stage 4), new aerobic microorganisms slowly replace the anaerobic forms and re-introduce oxygen to the region. Microorganisms that convert methane to carbon dioxide and water may also become established (Barlaz and Ham, 1993; Nikolova, 2004). As biodegradation reaches Stage 5 and aerobic conditions return, the leachate will eventually cease to be hazardous to the environment (Hester and Harrison, 1995).

Another further process that may occur during, and extending, the stage-3 biodegradation phase, is that of sulphate reduction. The sulphate reduction process requires the presence of sulphide and volatile fatty acids (VFAs) in adequate concentrations in the leachate; soluble sulphide may be derived from the inorganic fraction of the waste and VFAs from the result of biodegradation of the organic fraction. Where sulphate reduction processes are occurring, methanogenesis will be partially or totally inhibited by competition from sulphate-reducing bacteria for the available organic carbon and H_2. Once sulphate reduction becomes established, the toxicity of soluble sulphides (e.g. hydrogen sulphide (H_2S)) further inhibits methanogenic activity (Wheatly, 1991).

In a study of leachate quality at large landfills (those that receive between 0.5 and 1.0 M tonnes of MSW, commercial and industrial wastes per year), Robinson (2005), presents data that show the leachates being generated during the stable methanogenic phases of waste degradation are extremely similar and indistinguishable from any other landfill leachates worldwide. This despite the often significant differences in the composition of the wastes at individual landfills, the climate of a particular country, including seasonal variations in rates of rainfall and temperature, the quality of landfill management applied to a given site.

3.3.2 Microbial clogging of granular drainage media – field studies

Over time, the performance of the basal landfill collection system can deteriorate due to the build up of microbial clog deposits and sediments in the drainage gravels and perforated pipes (e.g. Brune, 1991, Rowe *et al.*, 1995). If similar processes occur in the filter pack, well screen and waste directly around vertical wells, then a reduction in the performance of the well over time would be expected, and if total occlusion occurred, then the well would no longer function. Field and laboratory studies of aggregate clogging will be discussed below. Although these studies are concerned primarily with the clogging of basal landfill drains, the processes and mechanisms that are occurring may also be applicable to vertical wells.

Brune *et al.* (1991), carried out a field investigation of a number of landfills in Germany where significant clogging in basal leachate collection systems had been observed. A survey of 29 MSW landfill sites with leachate collection systems showed deposits of incrustation material in more than half of the cases investigated. It was suggested, that the rapidly filled sites, showed more evidence of clogging than the older, slower filled landfills, though no rates of filling were given. Where deposits were observed, the degree of incrustation ranged from thin layers on the sides of drainage pipes, to extensive incrustations which blocked the entire pipe cross-section. Where possible, samples of the clog material were taken for analysis (Table 3.3).

At a number of sites, parts of the drainage system were exhumed and it was revealed that layers of waste above the drainage system had become consolidated and impermeable. No waste depth data are given by Brune *et al.* (1991), but it is possible that the consolidated waste and reduction in permeability observed in the waste above the drainage blankets may also be a consequence of consolidation due to depth of burial and not solely due to the formation of clog material.

From their field investigations, Brune *et al.* (1991) concluded that, in the landfills studied:

- metabolic activity of anaerobic bacteria is the main cause of clogging,
- microbiological processes are the most significant cause of incrustation,
- the main components of the incrustation material are the cations of calcium and iron, combined with carbonate and sulphide,
- the highest concentrations of organic and inorganic substances in the leachate and the greatest annual amount of drain incrustation were associated with the landfill that was filled most rapidly.

The rate of landfill filling may affect the clogging rate, because the microbial loading of the leachate passing through the drainage media will be greater in rapidly filled landfills (which will contain – at a given time - more organic material), than landfills filled more slowly. The biological loading of leachates was a significant cause of aggregate clogging in laboratory tests carried out by Paksy *et al.* (1998).

Similar field investigations were carried out by Rowe *et al.* (1995) and Fleming *et al.* (1999), to examine parts of the leachate collection system at the Keel Valley Landfill, Ontario, Canada. The collection system consisted of a continuous drainage blanket that had been in operation for between 1 and 4 years. The clog material included a significant portion of fine gravel, sand and other particles, assumed to have been washed from the overlying waste and trapped by the biofilm. Much of this clog material appeared to have been cemented by a calcite rich mixture of minerals derived from the leachate. In the lower, saturated, portion of the stone layer, Fleming *et al.* (1999), reported a decrease in hydraulic conductivity of approximately three orders of magnitude. The composition of the clog material recovered by Rowe *et al.* (1995) and Flemming *et* al. (1999), is shown in Table 3.3. The material composition is very similar to that given by Brune *et al.* (1991).

	% of total dry mass				
	Ca	**CO_3**	**Si**	**Mg**	**Fe**
Brune *et al.* (1991)	20	35	13	1	9
Flemming *et al.* (1999)	20	30	21	5	2

Table 3.3. Comparison of clog composition, (VanGulck & Rowe, 2004)

From the exhumations, Fleming *et al.* (1999) demonstrated that the accumulation of clog material (which included both organic and inorganic material) was greatest near the leachate collection pipe, decreasing with distance away from the pipes. They proposed that the increased rate of clogging was due directly to the higher flow of leachate in the immediate vicinity of the leachate collection pipe (i.e. due to the higher organic loading per surface area of aggregate).

3.3.3 Microbial clogging of granular drainage media – simulated, column studies

Following on from the field studies and exhumations, Brune *et al.* (1991) conducted laboratory tests to investigate the influence of leachate quality and drainage aggregate size on the encrustation process. The tests were conducted in columns, each packed with a different grade of filter aggregate (2-4, 2-8, 16-32 and 1-32 mm) and overlain by composted waste. High strength leachate was pumped in downward flow, at a constant 30 °C, through the waste and filter for between 10 and 18 months.

During the course of the experiment, the finer filter materials (2-4 mm and 2-8 mm) and the well graded stone (1-32 mm), suffered almost complete loss of permeability, with a 20 percent reduction in porosity. The medium-sized filter material (8-6 mm) experienced a 8 to 10 percent reduction in porosity, and the coarse filter (16 to 32 mm) experienced a 5 percent reduction in porosity. Close examination of the fine and well-graded drainage medias, showed that voids between pores were almost completely filled with incrustation material. Although the medium gravel was described as being extensively covered with thick biofilm and was locally clumped together, the coarser pores were still open. Individual grains in the coarsest filter material had some incrustation depositions but voids were not completely clogged and maintained their permeability (Brune *et al.*, 1991).

The tests were repeated with low strength leachate through medium size (8-16 mm) and coarse (16-32 mm) drainage aggregate. In each case, there was no significant reduction in porosity and permeability during the course of the experiment, suggesting that leachate strength is the controlling factor.

A similar investigation is described by Paksy *et al.* (1998). 12 laboratory columns were operated under anaerobic conditions for between 400 and 800 days. A reduction in the drainable porosity, due to the growth of microbial biomass in the pore spaces of the filter media, of between 1 and 12 percent was observed. The investigation was designed to examine the effect of flow rate, leachate composition, saturation conditions, mineralogy and particle size of the drainage material, on the degree of aggregate clogging. The research can be summarised as follows:

Particle Size and mineralogy - The typical particle size D_{10} of the drainage material was identified as one of the key factors governing the rate of clogging. No significant decrease in porosity was observed in the columns containing drainage materials in the largest size range, 20-40 mm. The porosity of aggregates less than 10 mm in size fell ‘significantly and rapidly’. For the intermediate size range (10–20 mm), a slow but steady decrease in effective porosity was observed. Paksy *et al.* (1998) conclude that as the smaller particle sizes experienced greatest accumulation of clog material, a minimum D_{10} of 10 mm is recommended for leachate drainage material.

Two mineral types were used as drainage materials in the columns – limestone chippings and Thames gravel. No significant difference in performance was apparent between the two materials. Paksy *et al.* (1998) conclude therefore, that the physical and chemical properties of the drainage material probably had little effect on the clogging process, and suggest that after a biofilm had developed on the aggregate, the properties of the original material may be irrelevant.

Leachate composition – synthetic leachates were used in most of the column tests. Variations in the composition of the leachate, which were characterised by their concentration of volatile fatty acids (VFAs), were assumed to be responsible for different degrees of clogging in the columns. Paksy *et al.* (1998), suggest that this is because the total concentration of VFAs, and therefore the biological loading of each column, was different for each leachate used.

Saturation conditions - in columns operated in saturated conditions, the increase in clogging was generally most significant in the zone closest to the inlet. In unsaturated conditions, the increase in clogging rate became more pronounced towards the outlet. The average clogging rates were slightly greater in saturated than unsaturated conditions with the greatest degree of clogging observed for sections of the column subjected to alternating periods of saturated and unsaturated flow. Paksy *et al.* (1998) concluded that it would therefore be preferable to operate a real landfill drainage system saturated because this would be easier to maintain than a continuous and uniform state of non-saturation.

Biological load – the biological load was controlled by both increasing the infiltration rates through the columns and by increasing the leachate strength (VFA concentration). On increasing the biological load, an increase in the rate of clogging was observed, with a reduction in the drainable porosity of the filter material of up to 4 percent (Paksy *et al.*, 1998).

Rowe *et al.* (2000) also investigated the influence of aggregate particle size on clogging processes. Laboratory columns were packed with uniformly graded glass beads in saturated, anaerobic conditions. The aggregates (glass beads) had initial drainable porosities of 0.37 (4 mm aggregate), 0.38 (6 mm aggregate) and 0.50 (15 mm aggregate). After 165 to 171 days, the tests indicated that the columns containing 4 mm and 6 mm beads failed due to the accumulation of clog material in the lower half of each column, near the column inlet. The column containing 15 mm beads appeared to have clogged due to a more consistent accumulation of clog material along the entire column length. They suggest that this is because the clogging had occurred over a similar surface area in each column – close to the inlet of the column for the smaller particles that had a large surface area per unit volume and over the entire column for the larger particles. This differs to the results offered by Paksy *et al.* (1998), in which biological clogging was greatest near the inlet, even for larger aggregate particles. However, the total VFA concentration (biological load) of the leachate used in the tests carried out by Paksy *et al.* (1998), was much lower than that used by Rowe *et al.* (2000). The results of each investigation may, therefore, not be comparable. Recent investigations by Rowe and McIssac (2005), observed a more uniform distribution of clog material in a gravel column that had experienced upward flow of leachate for almost two years.

From the experimental work, Rowe *et al.* (2000), suggest that operating filters in unsaturated conditions will help prolong the life of the filter by reducing the extent of microbial growth. When leachate wells are pumped, the aim of the well may be to dewater the landfill, with pumps placed at the base of the well to achieve maximum drawdown in the waste. Paksy *et al.* (1998), concluded that although unsaturated conditions were more favourable (in reducing the extent of biological growth), saturated conditions would be easier to maintain and that this is more realistic for landfill environments.

3.3.4 Implications for leachate well pumping

Since new waste will generally be deposited on top of older material, in poorly-drained landfills, leachate characteristic of the aerobic stages of decomposition may not be observed. Liquid percolating through fresh and then older waste will reflect the characteristics of the older waste, which may be in any of the other four stages of decomposition (Barlaz and Ham, 1993). If, however, the basal drainage layer is kept well-drained, high strength leachate produced in the upper parts of the landfill will pass, 'undiluted', through the drainage aggregate. This may be acetogenic leachate with a high biological loading from the early stages of waste degradation, even if the waste directly above the drain is mainly methanogenic. Leachate wells, by contrast, will drain leachate only from saturated waste, which is more likely to be homogeneously methanogenic. Basal drainage layers may, therefore, be more prone to clogging than wells, owing to the potentially higher strength leachate passing through the aggregate.

Investigations by Paksy *et al.* (1998) indicate that the size of the aggregate used as the drainage media will determine the extent of microbial clogging. They conclude that if the rate of nutrient supply provided by the leachate is sufficient, a drainage material comprising aggregates with a D_{10} size of less than 4 – 6 mm will be susceptible to microbial clogging within a few years of operation. This could have significant design implications for vertical wells if a fine grained filter material is necessary to prevent material ingress, and could limit the use of traditional filter rules (Section 3.4.3) in choosing filters for landfills. Where finer filters have been used in landfill wells (in the data base, filters range from 5-40 mm), microbial clogging may accelerate the loss in performance, though the rate of clogging will also be related to the biological loading of the leachate and the of time.

3.4 Physical clogging and sediment deposition

Physical clogging is the reduction in material permeability by the redistribution of particulate matter, which can affect the aquifer and the well (Howsam, 1990). The processes involved can include:

- damage to the formation at the time of construction (well skin),
- the inter-mixing of aquifer and gravel pack material due to over aggressive development and pumping,
- the migration of fines from the aquifer towards the well and into the gravel pack material,
- migration of aquifer material into the well causing it to be infilled (sedimentation)

3.4.1 Well skin

When a well is drilled, smearing and milling around the borehole walls, and localised compaction of the waste, may reduce the permeability of those areas. This is termed the well skin and is defined as the imperfect hydraulic connection between a well bore and the well structure and/or formation outside the borehole (Barrash *et al.* 2005). The well skin acts as a filter in series between the borehole and the undisturbed formation, and will result in head loss and changes in radial flow patterns during pumping (Young, 1998). Over time, further clogging may occur due to physical plugging of pores by solids, precipitation of insoluble materials in pore spaces, clay swelling and the migration of fines.

As such, well skin causes either an additional resistance to flow (positive skin) if it has a lower hydraulic conductivity than the undisturbed formation, or causes a lessened resistance to flow (negative skin) if it has a higher hydraulic conductivity than the disturbed formation. Powrie and Beaven (2003), assessed the performance of a number of individual landfill wells, using analytical methods developed by Barker and Herbert (1992a and 1992b) for well losses. The analyses indicated that at relatively low flow rates, non-linear well losses (i.e. those around the pump inlet, inside the well screen) can generally be ignored. Linear well losses, however, such as those resulting from disturbance to the waste during drilling or a clogged filter pack could be significant.

3.4.2 Sedimentation

Sedimentation occurs when soil and waste particles drawn through the well screen settle and accumulate in the bottom of the well, reducing the well's effective depth. Sediment deposited in the base of a well will prevent a pump from being installed at the lowest possible elevation, reducing well yield and the drawdown available. Sediments drawn into the well bore can also lead to premature pump wear and clogging of pumping infrastructure. Sedimentation requires both a source of fines, a mechanism by which they are transported, and a mechanism by which they can be deposited. Furthermore, sand and gravel from the filter pack can enter the well screen if the grain size distribution is too small or the screen slot size is too large. Once particles have entered the well bore they will settle out if the flow is insufficient to keep them entrained. Sedimentation appears to be common in landfill leachate wells. In the vertical well database, where current base level data was given, base levels (calculated as the original drill depth of well less the most recent base level of well) had increased to some extent in over 80 percent of the wells, between 0.1 m to 11.8 m, with an average increase of 2.6 m.

In groundwater wells installed in unconsolidated formations, sedimentation is usually attributed to the sloughing of particulate material from the formation under the turbulent flow conditions induced by well development and pumping (Wendling *et al*, 1997). Also, when a well is pumped for the first time after an extended period of non-pumping, there will be an accumulation of both sedimentary and sloughing particulates within the waster phase which will be removed preferentially by the initialisation of the pumping (Howsam, 1990). This will also occur in landfill wells, especially low yielding wells which may be pumped on a stop-go basis. The leachate stored within the well bore and gravel pack is pumped out rapidly, but as recharge is slow, the pump will switch off until the leachate level has recovered. Intermittent pumping of this nature – rapid draw-down followed by periods of recharge - may, over time, contribute to clogging in the well pack. The high rate of pumping will lead to relatively high fluid velocities through the slotted inner casing and the inner sections of gravel pack annulus, mobilising fine waste pieces and soil material in the immediate vicinity of the well. When the pump stops as the leachate is drawn down below the pump inlet, particles in suspension within the gravel pack and waste may settle into voids and may not be dislodged by further pumping (Joseph, 1997). The higher the rate of pumping, the greater the radial distance from the well over which fines may be mobilised.

When material collects in a well bore, the effective saturated depth is reduced by restricting the depth that pumps can be installed to. This is demonstrated in Figure 3.4. This will, over time, result in a reduction in well performance as base levels rise due to sediment deposition. If the saturated depth of the waste is reduced through dewatering, the effective depth of the well will also be reduced further.

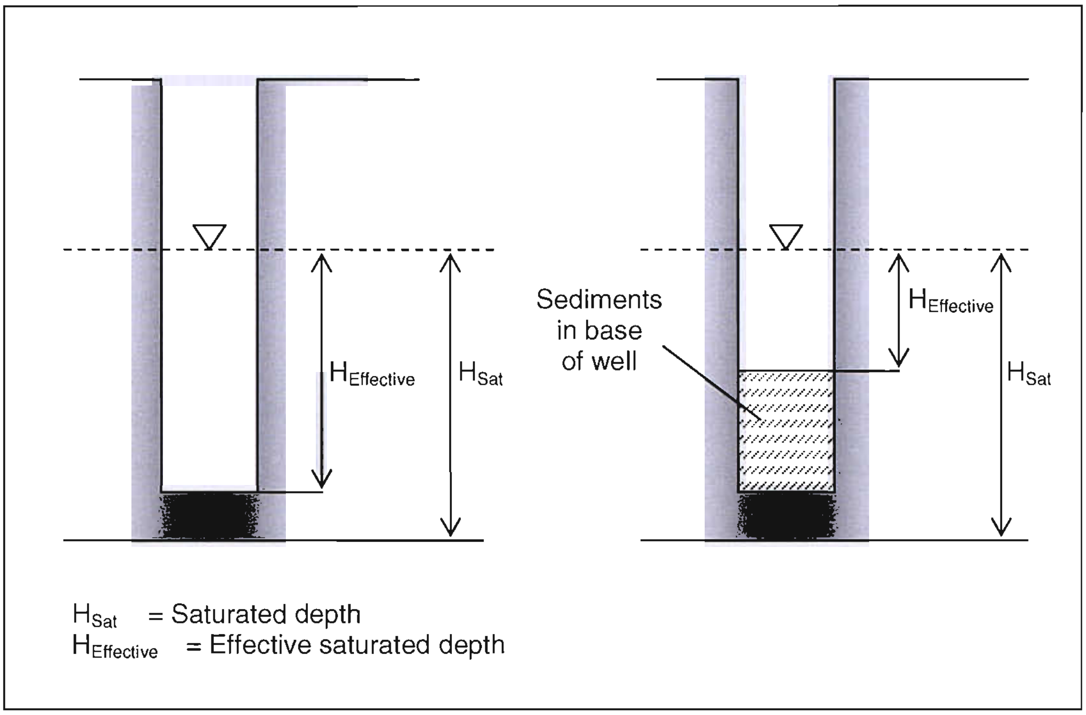

Figure 3.4. Reduction in effective depth due to sediment ingress

3.4.3 Well design – filter pack

When installing wells for groundwater abstraction, a suitably designed well installation incorporating a fine-grained filter pack and narrow slot-size is often used to prevent fine particulate material from entering through the well screen. Investigations into the optimum filter pack grain size for use in granular soils have been undertaken (e.g. Sherard *et al.*, 1984a and 1984b). Different filter grades were tested in laboratory apparatus to determine the ideal pack / aquifer combination to prevent the movement of fines into a borehole. Based on such analysis, Driscoll (1987) and Preene *et al.* (2000), for example, give recommendations for choosing filter packs based on the particle size distribution (PSD) of the formation. These provide filters that are:

- fine enough to prevent the persistent movement of fines from the aquifer ($D_{15filter}$ $5 \times D_{85aquifer}$),
- coarse enough to be significantly more permeable than the aquifer ($D_{15filter} > 4 \times D_{15aquifer}$),
- sufficiently uniform to allow installation by depositing underwater with minimum risk of segregation ($C_{u\ filter} < 3$).

In a landfill, calculating or estimating the PSD is complicated by the heterogeneity of the waste. Large variations could be expected across a site and, as waste degrades and compresses, the grading envelope (combination of PSD curves from a particular formation) would be expected to become finer over time. Horizons of fine-grained, granular cover soils between lifts of waste may also be present. The above criteria would recommend the filter choice should be based on the finest formation grading, which may be the cover soils.

The diameter of the well and the well screen, and the width of the well annulus, is less important than the choice of filter media. Granular filters have been shown to be effective when as thin as 12 mm (Driscoll, 1987). Sherard *et al.* (1984a) also conclude that angular particles of crushed rock are as suitable as rounded alluvial particles for filters and can be designed using the same criteria.

3.4.4 Well design – well screen

The size of the slot openings of a well screen is generally governed by the grain size distribution of the filter pack, or (if no filter pack is present) of the formation. If slots are over-sized, then fines from the formation and filter pack will be able to mobilise into the well. If slot openings are under-sized, then there will be a greater resistance to flow and more head loss, leading to possible corrosion and clogging (Driscoll, 1987). Driscoll, recommends the use of a slot that retains the D_{10} of the filter pack media.

Bonaga (2000), describes a series of laboratory experiments to investigate the influence of well screen slot width on the ingress of waste particles into a pumped well in a landfill. The effect of differing waste densities and leachate extraction rates was also investigated. Screens with slot sizes varying from 0.5 mm to 2 mm were tested. Samples of aged domestic waste were recovered from approximately 10 m depth, from an active landfill. Analysis indicated a water content of 68 percent and a PSD covering a range between 100 mm to 63 μm. The waste was packed to various densities around the well screen within a 0.34 m diameter ring of wire mesh. This created a 40 mm annulus between the outside of the mesh and the inside of the tank into which water could be introduced. Water was pumped out of the well screen at rates varying from 2 to 30 litres/min (equating to entrance velocities through the screen between 0.0007 and 0.0027 cm/sec), and passed through a filter into a collection tank. The head in the well was recorded at steady-state and samples of sediment trapped in the filter taken after 15 minutes pumping.

At low densities, for all slot sizes, the mass of particles washed into the well could be related to entrance velocities. For a given flow rate, more material was washed through the smaller slot-size (with a correspondingly smaller open area) than the larger slot sizes, with larger open areas. There was little difference in the particle size distribution and composition of the material collected from the tests with different sized slots. A comparison of the water level in the well screen at varying flow rates indicated larger well losses through the smaller 0.5 mm slots than through the larger sizes. However, if the data is normalised against entrance velocity, although well losses still increase with velocity, there is little difference between slot sizes. At higher waste densities, a less comprehensive suite of results were obtained and no clear relationships were evident, though for a given flow rate or entrance velocity, more material was washed into the well than at the lower waste density (Bonaga, 2000).

3.4.5 Implications to landfill well design

The process of drilling a borehole in a landfill, may create a well skin with a lower permeability than the surrounding waste. The extent that this may be occurring is unknown, though numerical analysis by Powrie and Beaven (2003) suggest that well losses through skin effects in leachate wells could be significant.

Suspended material carried towards the well, may be filtered from the leachate by the filter pack, the well screen, and the waste itself. Over time, this material will collect in the waste and filter pack around the well, lowering the permeability of these zones, increasing head losses and reducing the performance of the well.

To limit the movement of fines from the waste, a filter pack will be used in the well annulus. For basal landfill drainage, Paksy *et al.* (1998) recommend a D_{10} size of at least 10 mm to guard against biological clogging. Experiments by Terzaghi *et al.* (1996), have shown that aquifer particles smaller than $0.1 \times D_{15filter}$ can pass through a filter. In the vertical wells database, the filter pack grain size ranged between 5 and 40 mm, with over 40 % of the wells installed with a 20 mm pack. The D_{15} of a 20 mm gravel is approximately 10 mm. A 20 mm gravel will theoretically therefore, permit a particulate size of approximately 1 mm (and smaller) to pass into the well. A finer-grained filter pack would permit less fines, but may risk microbial clogging. Therefore, it may be that a compromise is needed between a filter pack grade to prevent the movement of fines and a grade to prevent microbial clogging.

Laboratory tests carried out by Bonaga (2000), suggest that there is little advantage in using a small slot size to filter waste where a larger slot size will be more efficient. Instead, to filter fine waste and soils a filter pack should be considered, with screen slots sized to prevent the movement of the filter pack into the well. The investigations have demonstrated that at low waste densities (i.e. such as might be found in uncompacted fresh waste, in shallow landfills or in the upper parts of deeper landfills), the screen slot size had no influence on what material type and size that was filtered; the larger slot sizes were as efficient at filtering material as the smaller slots. The well screens with the smaller slot sizes, however, experienced greater well losses. Bonaga (2000), concludes, that owing to higher entrance velocities, more material was washed through the screens with the smaller slot sizes. At higher waste densities (i.e. such as might be found in older, deeper landfills) the investigations were less conclusive. However, for a given flow rate more material was washed into the well than at the lower waste density.

Current leachate well design permits the migration and deposition of fines in the well bore. 80 % of the wells in the database showed some sediment deposition, up to 12 m from the original installed base of the well. This will restrict the depth to which leachate pumps can be installed to, and so reduces the effective saturated depth of the well.

3.5 Well development

As discussed in Section 3.4, smearing of the well bore and the ingress of sediments into the near waste and gravel pack during drilling and pumping will decrease the permeability of these regions and alter the hydraulic performance of the well. Sediments that are drawn into the well may settle out of the leachate column, building up over time within the well casing, often to significant depths, restricting the depth of pump installation.

The purpose of well development is both to clean out sediments that may have been drawn into the well during pumping, and to alter the physical characteristics of the aquifer near the borehole in order to allow leachate to flow more freely toward the well. Well development will remove fine sediments and fine waste pieces from along the well screen-aquifer/well screen-filter pack contact and some distance into the waste formation. Traditionally, in the groundwater well industry, well development is carried out soon after installation and before pumping commences (e.g. Howsam, 1990). The information collected in the leachate well database, suggests that well development is rarely, if ever carried out directly after a new well has been installed in waste sites. Indeed, as it is often the accumulative effects of clogging that require remediation, well development is usually not carried out until yields have fallen, or sediment ingress is significant, which may be after some years of service.

The development of wells can therefore be subdivided into two categories:

Well completion development - Drilling a borehole and installing a well creates a zone of damaged formation material with reduced hydraulic conductivity compared with that of the adjacent undisturbed formation. Development aids repair of the damaged formation and may cause rearrangement of the local formation resulting in the increased hydraulic conductivity of material surrounding a well (Driscoll 1987). The immediate development of a completed well in landfill may therefore be essential to maximise the yield from the well.

Rehabilitation development - Despite the development of a completed well, continual degradation of the waste formation with time may liberate material of a composition and size that will be continually drawn into a well bore by pumping. It is therefore probable that wells in landfill will require additional redevelopment throughout their lifetime.

Development, involves alternatively surging and pumping to achieve a flow reversal into and out of the well through the screen and filter pack. This washing action dislodges drilling debris and fine soil particles, flushing them into the well screen. A variety of techniques are used to develop groundwater wells, though not all will be suited to the landfill environment. A brief explanation of the common techniques, with suggestions for their application to leachate wells, is given below.

3.5.1 Mechanical techniques

Surging: A tight-fitting plunger, or surge block, attached to the end of a length of drill rod or drill stem, is continuously raised and lowered within the leachate column. The up-and-down plunging action forces water to flow alternately into and out of the well, agitating and mobilising particulates around the well screen. Periods of surging should be alternated with periods of bailing or lifting, so that any sediments brought into the well can be removed. Surging should initially be gentle, to make sure leachate can flow freely into the well and that the surge block is not so tight as to damage the well casing or screen.

Bailing: A bottom-loading bailer with a tight-seal clack valve is repeatedly raised and lowered at the base of a well, often from a cable-driven drilling rig. The bailer will extract any sediments at the base of the well and any sediments drawn into the well during development. The diameter of the bailer should be close to the internal diameter of the well screen. The bailer will then agitate the water in the well in the same manner as a surge block, but to a lesser extent. To have its most effective surging action, the bailer should be raised/lowered throughout the entire screened section of the well.

3.5.2 Pumping

Over-Pumping: The well is pumped at a higher rate than it would be during normal operation, thereby mobilising sediments and fine pieces of waste into the well that would otherwise remain in the formation, pack or well screen. Material drawn into the well during over-pumping can be removed either by pumping or bailing. A disadvantage of pumping the well in a way that induces flow only towards the screen, is that small sediment particles carried in suspension from the waste might lodge in the screen and pack, reducing the efficiency of the well. Overpumping is therefore often used in conjunction with backwashing or surging.

Backwashing: Backwashing is the reversal of water flow in the well, causing sediment and waste particles that may have become wedged around the screen by overpumping of the well to dislodge. A commonly used backwashing technique consists of starting and stopping a pump intermittently to allow rising water in the well casing to fall back into the well. This backwashing procedure produces rapid changes in the pressure head within the well. Another method of backwashing is to pump water into the well to maintain a head greater than that in the formation, resulting in flow out of the well into the aquifer. After backwashing, any sediments drawn into the well during normal operation can be removed through bailing or pumping.

Jetting: Horizontal jets of water are directed at the inside of the well screen so that high-velocity streams of water exit through the screen and loosen fine-grained material and drilling mud residue from the waste formation. The loosened material moves inside the well screen and can be removed by pumping or by bailing. Jetting rearranges and breaks down bridging in the filter pack, and removes mud cakes around the well screen. Jetting is less effective in wells that have been installed with slotted well screen, and is most effective where continuous-wrap v-wire screens, having a greater open area, are used.

The two most commonly used groundwater well development methods are air surging/lifting and surging/bailing using drilling equipment (Howsam, 1990, Wendling *et al*, 1997). For landfill wells no published data is available, and the database suggests that development is rarely, if ever, carried out on landfill well installations. The development method should therefore be selected according to the characteristics of the well to be developed such as flow rate into the well, size and composition of particles entering the well and volume of sediment entering the well. Landfill wells often have a limited saturated depth, and generally low flow rates (Table 2.1). The available liquid for air surging/lifting may, therefore, be limited. Additional water may have to be pumped into a well to achieve optimum well development using this method. If an entire well field is to be developed, the addition of large volumes of water into a landfill may be considered imprudent and may be logistically difficult. The most suitable development method for the majority of previously pumped vertical wells in landfill is therefore likely to be lifting / surging of sediment and leachate using a shell operated by a cable-percussion drilling rig.

From well development tests in unconsolidated materials, Wendling *et al.* (1997), conclude that the head differences caused through surging were not a function of the screen slot size. Surging and bailing are therefore suitable for most landfill wells, although the screen loadings developed during surging can be very intense and the technique is not recommended for use in plastic well liners, unless thick-walled screen has been used (Preene *et al.*, 2000).

3.6 Key findings from literature review

- the low hydraulic conductivity of waste and variations in hydraulic conductivity, spatially and with depth, may ultimately be the controlling factor in the amount of leachate that can be extracted over a given period of time from a landfill well. The hydraulic conductivity of landfill waste is low, and will decrease further with depth of burial. In deep landfills, the difference can be up to four orders of magnitude.

- Investigations of microbial clogging of drainage media suggest that the controlling factors are particle size and biological loading. Simulated clogging tests recommend a filter size with a $D_{10} > 10$ mm. No investigations have been carried out in vertical landfill wells.

- A well skin may be formed by the drilling process, though the extent that it will affect the performance of a landfill well is unknown. Physical clogging can occur during pumping, and the deposition of material in a leachate well bore is common. It is unknown whether this is because wells were not developed on installation, or because of a more fundamental problem with well design.

- The deposition of material in the well bore is common. This will reduce the effective saturated depth of the well.

- Well development is not routinely carried out in landfill wells, and new wells are not developed when they are first installed.

3.7 Chapter Summary

The low hydraulic conductivity of landfilled waste, coupled with the combined effects of biofouling, precipitation and encrustation in the gravel pack, around the slotted casing and in the surrounding waste, are not conducive for high volume leachate yields. The extent to which these factors affect the performance of a well is a function of the nature of the waste, the chemical make up of the leachate passing through the well and of time.

Over time, flow toward the well may decreases as a result of clogging, compaction and dewatering in the waste mass. The well will experience a loss in productivity, or an increase in drawdown in the well for a given extraction flow rate.

The clogging mechanisms of aggregates in landfill drainage are reasonably well-established, and although previous studies have focused on basal drainage systems, the processes involved are also applicable to vertical leachate wells: the blockage of pores by the accumulation of organic and inorganic clog material that reduces the hydraulic conductivity of the porous media. Exhumations of basal leachate collection systems have shown that clogging is extensive and can greatly reduce the effectiveness of a drainage aggregate. Laboratory tests have demonstrated that the rate of clogging is proportional to the biological loading of the aggregate. For example, in column studies, highly loaded leachate induced extensive clogging of the drainage material, while lightly loaded leachate caused almost no incrustations (Brune *et al.*, 1991). The aggregate particle diameter also has a significant impact on the rate and extent of clogging. Rowe *et al.* (2000) suggest that this is primarily due to the increased pore size associated with larger particle sizes, that increase the time required for occlusion of pore spaces.

As the waste compresses under loading and dewatering, the hydraulic conductivity will fall. The greater the depth of burial, the greater the degree of compression and the greater the reduction in hydraulic conductivity. Within the landfill, the lowermost waste will therefore have the lowest hydraulic conductivity, yet it is this area that requires dewatering. As the waste dewaters, and leachate heads are reduced within the waste, the performance of a well will therefore decline at a rate greater than due to dewatering alone. Over time, as the waste degrades, the hydraulic conductivity of the material may decline further, again reducing the performance of wells.

The effective saturated depth of a well will be reduced over time as leachate heads fall through dewatering and if sediments that migrate into the well are deposited in the well bore. The well development techniques used in the groundwater industry may be applicable to landfill wells. Yields from newly installed wells may be improved by immediate development, wells that have become clogged with ingressed sediments may be remediated..

When designing new wells for use in a landfill, a compromise may have to be made between the ideal well design to limit well losses, a design that filters fine grained material from being washed into the well, and one that is not prone to microbial clogging. It may, for example, be better to install a well with a coarse gravel pack that will be less prone to microbial clogging, but may allow the movement of fines into the well. If the well does become clogged with deposited sediments, then well development techniques can be used to clean the well and improve yields.

Chapter 4 describes, with reference to the above discussions, field investigations of existing leachate wells. The aim of the investigations was to seek evidence of microbial clogging and sedimentation, and relate it to the well design, performance and installation technique.

Chapter 4

Visual observations of existing wells

4.1 Introduction to Chapter

The investigations described in Section 3.3 have demonstrated that over time, as a result of the biological load of typical landfill leachate, microbial clogging will occur in aggregates used in leachate management systems. Exhumations of basal drainage systems (e.g. Brune *et al.*,1991), have also demonstrated the potential for clogging of perforated drainage pipes. These studies have, however, only included basal dewatering systems, and not vertical wells. The extent and significance of clogging in filter packs and well screens in vertical wells is, therefore, unknown. If similar processes are occurring – the occlusion of aggregate void spaces by microbial deposits – then a loss in well performance would be expected over time, as the filter pack clogs and permeability is reduced. Also, if encrustations were forming on well screens, a reduction in open area will reduce flow, increasing drawdown.

In this chapter, a programme of field investigations of existing pumped leachate wells will be discussed. The investigations include down-hole CCTV surveys of a series of wells at different sites, and the exhumation of three wells from one site to observe the condition of the inner and outer casing and filter pack.

4.2 CCTV survey

To investigate and observe mineral encrustations and biological and physical clogging in existing landfill wells, a downhole closed-circuit television (CCTV) camera was constructed. The CCTV camera was fitted with two adjustable light sources, which could be focused to spot-light or over-light the inner well. The camera was fully water-proof, with an anti-fog coating on the lens. The CCTV camera arrangement is shown in Figure 4.1.

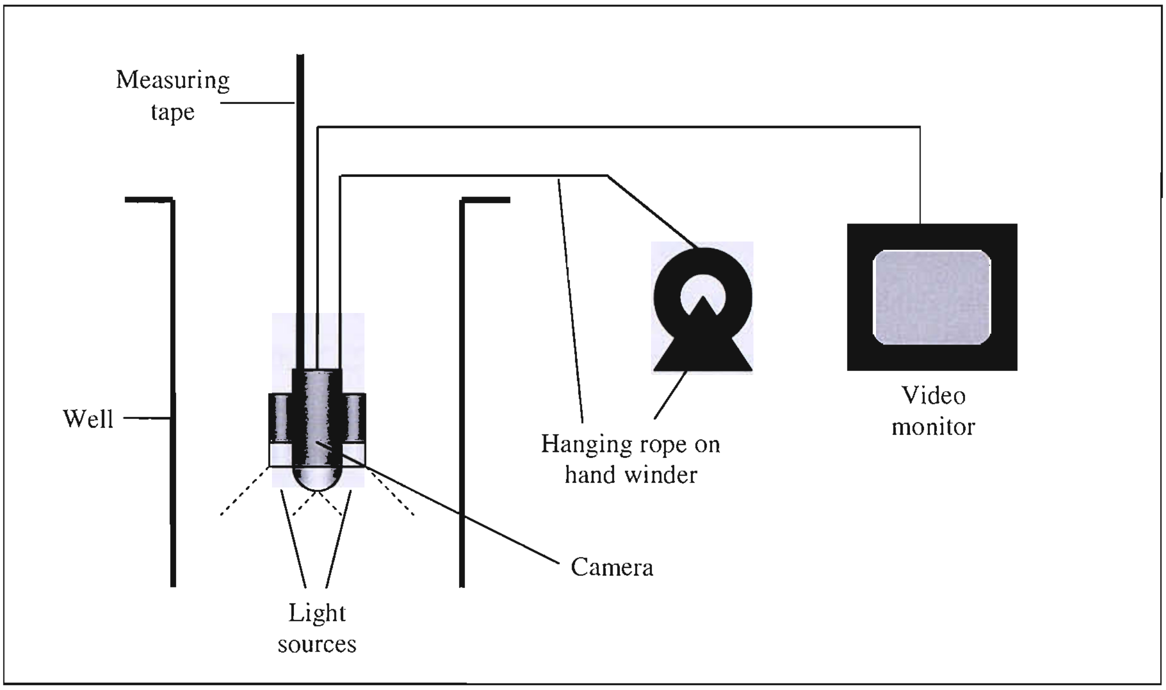

Figure 4.1. CCTV inspection arrangement

Although the camera and light sources were designed to operate fully submerged in leachate, sediments and deposits stirred up in the leachate column and the opacity of the leachate itself often resulted in visibility too limited for useful data collection. Where possible, leachate levels often had to be lowered in the well prior to inspection. Also, despite the anti-fog coating, water vapour and venting landfill gas could lead to condensation and misting of the lens. At depth this problem could be solved by submerging the camera briefly in the leachate. However, in the upper parts of wells, and in wells containing no leachate, it proved difficult to overcome.

4.2.1 Sample strategy

To provide a true estimate of the characteristics of a vertical wells across the UK, a suitable sampling procedure was required that would provide an accurate sample that resembles the population (i.e. all vertical leachate wells) as closely as possible. Three landfills were chosen for the CCTV survey, from which approximately 50 wells were selected at random from a site plan of each landfill. The three landfills were selected as they contained a choice of well installations with both plastic and steel well liners, historical pumping data for most of the wells, and where site operations would allow access to pumping equipment and the disposal of leachate (to draw-down leachate heads).

In the vertical well data base, approximately 70 % of the wells were installed with steel well screens and 30 % with plastic well screens. A quota-sampling technique was therefore used to include a representative number of both steel and plastic well installations. Before the CCTV surveys were undertaken, a walk-over survey was carried out at the four landfills to ensure that the wells selected were accessible to the CCTV equipment (those unsuitable included wells that rose too high above the ground or had pumping equipment installed that could not be removed). Where a well could not be used, if possible a different well, from the same site, was chosen at random, or if a replacement was not possible, the number of wells was reduced. In total, 26 wells from three landfills were inspected.

The wells presented in the survey, can therefore be described as being *essentially random* as true random sampling was not practically possible.

4.2.2 Observations from CCTV survey

Full details of the down-well CCTV survey are reproduced in Appendix B.

In all of the wells surveyed, staining was apparent on the inside of the casing. This was most pronounced at the joints between casing lengths. The staining varied in colour from black and white to orange. In some wells, the staining was seen to issue from individual well slots.

In the upper parts of many of the wells – above the leachate level - surface deposits were common and some form of mineral deposit was apparent on the casing walls of more than half the wells surveyed. These deposits were solid (they were not displaced or marked by contact with the camera), and where present, often fully coated the inside of the well screen.

In some of the wells surveyed, failure of the well screen meant that it was not possible to observe the full screened section of the well (for example, wells 203, DW1 and 384). Also, in some instances, encrustations around the well casing were present, but no slots could be seen. It was not possible to determine whether this is because the slots were obscured by encrustations, or because the leachate level could not be reduced to below the top of the well screen.

In the wells where the screened section of the well was visible above the leachate level, 80 percent of the wells showed some degree of encrustation occluding or partly occluding slots. For these wells, a visual assessment was made of the degree of slot clogging, i.e. how much of the slot by area was, on average, covered by encrustations. 0 % clogged describes a clean, fully open slot with no sign of precipitation, corrosion or clogging by waste material. 100 % clogged describes those slots that had become apparently completely closed by encrustations. A summary of these wells is given in Table 4.1, more detailed observations can be found in Appendix B. Only the wells where actual slots (closed or otherwise) were observed have been included in the table.

Two different forms of clogging and encrustation could be identified:

- surface corrosion and oxidation of the casing material,
- mineral precipitates coating the sides of the casing.

Although it was not possible to collect samples of the encrustation material, it can be reasonably assumed that in wells installed with a steel well screen, the material observed flaking from the sides of the casing and clogging slots was a result of the oxidation of the steel, probably hydrated iron (III) oxide. Superficial oxidation (rust) deposits were noted in the upper parts of all the steel well screens examined. More extensive oxidation of the steel was evident in the slotted screened part of the well above the leachate table. Oxidation products were responsible for the clogging of slots in over 80 percent of the cases that showed some degree of clogging.

Site	**Well No.**	**Casing type**	**% clogging**		**Observations**
			Below	**Above**	
Bromsgrove	805	Plastic	0	0	No clog deposits above or below leachate level.
Rainham	245	Steel	0	20 - 100	Slots directly within leachate fully open. Slots above leachate clogged by encrustations, increasing with elevation.
Rainham	328	Steel	0	0	No clog deposits above or below leachate level.
Rainham	338	Steel	0	15	Within and directly above leachate level, all slots open. In upper well, some encrustations.
Rainham	349	Steel	0	0	No clog deposits above or below leachate level.
Rainham	375	Steel	0	80	Slots directly within leachate fully open. Clogging in upper well above leachate zone.
Rainham	716	Steel	0	40	Slots directly within leachate fully open. Clogging in upper well above leachate zone.
Rainham	718	Steel	0	5	Slots below leachate fully open. Clogging in upper well above leachate zone.
Rainham	726	Steel	0	25	Slots directly within leachate fully open. Some degree of clogging in upper well.
Rainham	731	Steel	0	5 - 20	Slots within leachate fully open. All slots in upper well show some degree of clogging.
Rainham	734	Steel	0	15	Slots below leachate fully open. Some clogging in upper well.
Warnham	201	Steel	0	100	Slots within leachate fully open. Complete occlusion of slots in upper well.
Warnham	204	Steel	100	100	Complete occlusion of slots below and above leachate table.
Warnham	207	Plastic	n/a	100	Complete occlusion of slots in upper well. Can not see slots below leachate.
Warnham	217	Steel	0	100	Slots within leachate fully open. Complete occlusion of slots in upper well.

Table 4.1. Summary of slot clogging from survey above/below average leachate level

Precipitated mineral deposits were less common, though where they did occur they tended to completely coat the inner well screen occluding 100 percent of the slots. This is demonstrated in Figure 4.2. The image was taken at approximately 12 m below the top of the casing in well 207 at the Warnham landfill, Surrey, above the permanent leachate level.

Although no analysis was undertaken on the deposits in this well, previous work at this site (e.g. Board, 2001) would suggest that the material is calcium carbonate ($CaCO_3$).

Figure 4.2. Probable calcium carbonate precipitation on well casing above the leachate level. Well internal diameter approximately 170 mm (well 207, Warnham landfill)

It was apparent from the survey that, except for well 204, in wells that showed evidence of clogging and corrosion, the deposits were only ever present above the leachate table. Below the leachate table, slots were fully open and clear of deposits. For example, Figures 4.2 and 4.3 are images taken at different elevations within well 716, Rainham landfill. Figure 4.3 shows slots above the permanent leachate table, and Figure 4.4 below. In the unsaturated zone above the leachate table, slots are fully closed with precipitates. Those below show little or no deposits, and all slots are fully open.

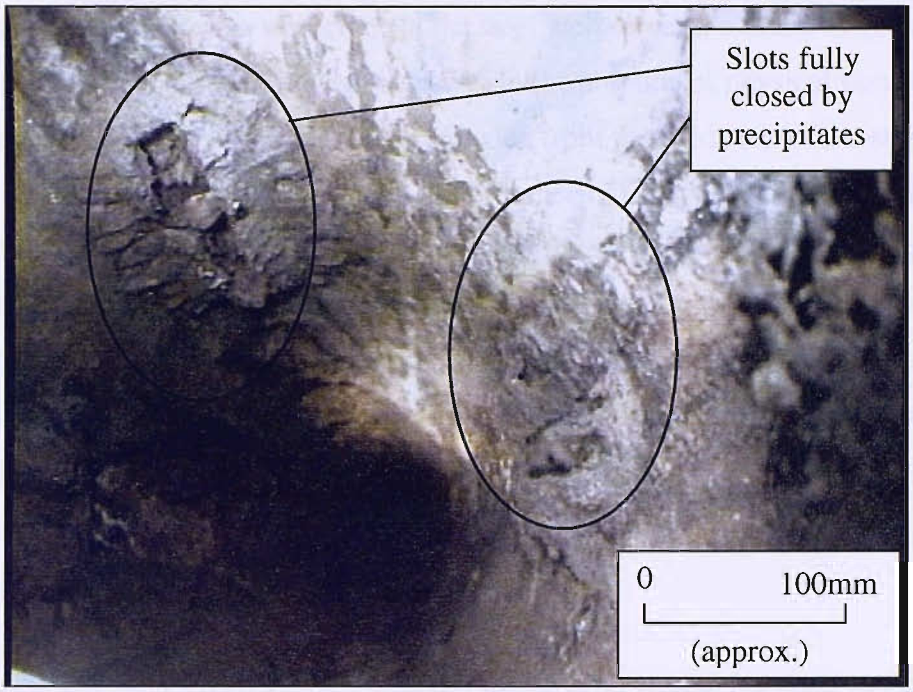

Figure 4.3. Fully closed well screen slots above leachate level (well 716, Rainham landfill)

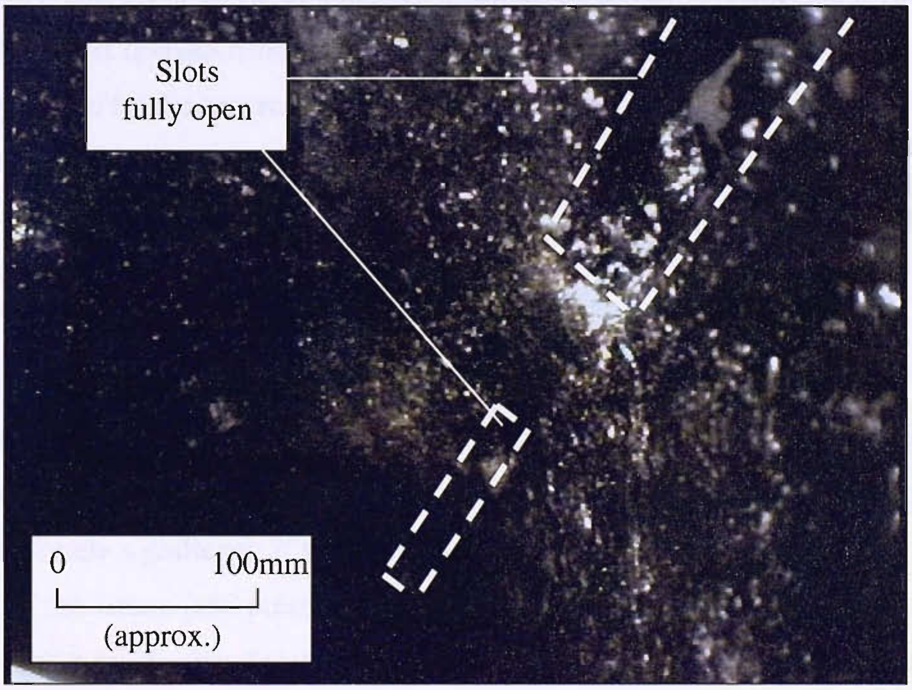

Figure 4.4. Fully open well slots (highlighted) below leachate level (well 716, Rainham landfill)

4.2.3 Survey summary – implications and limitations

Two encrustation types were observed. In the steel well screens, surface corrosion and oxidation of the casing material was extensive. In the absence of physical samples, the material is assumed to be hydrated iron (III) oxide from the oxidation of the steel well liner. This may have been accelerated by the presence of CO_2, present as a component of landfill gas (Section 3.3.1), in the head-space in the well above the leachate, and from gas condensates on the liner walls. Dissolved CO_2 in the leachate will form carbonic acid (H_2CO_3). The increased pH of the leachate (and in the condensate) may promote the oxidation and precipitation of iron oxides on the inner well casing (Davidson and Seed, 1983). No corrosion or encrustation was observed on the liner below the leachate, suggesting that the mechanism is a consequence of landfill gas in the head space above the leachate, rather than the leachate itself.

In both steel and plastic well screens, mineral precipitates coated the sides of the casing. The material is thought to be calcium carbonate (Board, 2001). Analysis of hard clog material collected from basal drainage media (Brune *et* al., 1999, Flemming *et al.*, 1991) showed the material to be predominantly Ca and CO_3 (Table 3.3), and x-ray diffraction analysis by VanGulk *et al.* (2003), has demonstrated that $CaCO_3$ collected from landfill drainage media is derived from the leachate. They suggest, that the precipitation of $CaCO_3$ is caused by the anaerobic fermentation of volatile fatty acids (VFAs), which adds carbonate to, and raises, the pH of the leachate (VanGulk *et al.*, 2003). Depressurisation of the leachate as it enters the well bore, will also lead to the precipitation of dissolved minerals (VanGulk *et al.*, 2003).

The CCTV well inspection has demonstrated that although encrustations were common in the leachate wells examined, they were only present above the permanent leachate table. Below the leachate level, slots were generally clear and free of mineral deposits. This is extremely significant: if wells are not clogging below the leachate table, then clogging of the screen (and presumably the filter pack in contact with the screen) can be discounted as a mechanism for well deterioration. Equally, where clogging does occur, unless 100 % of the slots are occluded, at low flow rates (<10 m^3/day), well losses will probably be insignificant (Powrie and Beaven, 2003).

The waste type and age was similar at the three sites, though the age of the wells varied (between 36 and 96 months in operation). The age of the well did not appear to have a significant effect on the type and amount of encrustation, though older wells showed a tendency to have a greater percentage of clogging than younger wells. This could be expected, because without a mechanism of removing the encrustations, the deposits would be expected to accumulate over time. It was not possible to conclude from the survey the time frame over which clogging would occur, though the rate and degree of clogging may be more a function of the age of the waste rather than of the well. Although the leachate chemistry in individual wells would not be expected to vary considerably (Robinson, 2005), the biological loading may have some influence on the degree of encrustation. Laboratory tests presented by Rowe *et al.* (1995), suggest that the rate of clogging (in vertical wells) is likely to be greater while BOD/COD (Biological oxygen demand/chemical oxygen demand) values are high and is likely to be significantly reduced as the BOD and COD fall. Wells installed in new landfills, with high BOD and COD (e.g. Stage 2 of biodegradation), are, therefore, likely to clog faster than those installed in old landfills. If wells do begin to clog, then providing the pack and screen within the saturated zone are open, then performance should not be affected.

4.3 Well Exhumation

Although useful for demonstrating the clogging potential of leachate wells from organic and inorganic precipitates, the downhole CCTV observations were restricted to internal observations and the condition of the outer well screen and gravel pack could not be assessed. In April 2002, a 250 m dewatering drain was installed in the Phase 1 Area of the Rainham landfill. The proposed line of the drain intersected three vertical leachate extraction wells, which would need to be removed from the landfill to allow access to the trench. The opportunity was taken during the excavation works to exhume the three wells, allowing observations of the borehole and the condition of the outer well screen and gravel pack.

The wells were installed during 1995 using 400 mm rotary barrel-auger drilling techniques, initially commissioned for landfill gas extraction. The wells were completed with 178 mm steel casing, partially screened (with vertical slots 10 mm x 100 mm, an open area of approximately 3 %), with a base plate. Gravel was installed around the well screen to 1 m above the leachate table (this varied between wells). Above this the well annulus was open to the surface. The upper 4 m of the well was sleeved with an HDPE well head, connected to a gas extraction main. A three metre bentonite seal was then placed around the sleeve, held in place by a skirt at the base of the cover.

Although the wells were connected to a landfill gas collection main, the wells were allowed to vent freely to atmosphere, and no active gas extraction was undertaken. Each well had been installed with a proprietary air-fed pump fitted with a pump-cycle counter, allowing the yield of each well to be monitored. This system operated continuously for approximately 400 days until the wells were exhumed. The average yield was around 0.5 m^3/day.

The wells were exhumed in two stages, using an excavator working from a middle work platform (Figure 4.5). Firstly, the upper length of casing and well bore were exposed to the work platform. After removing all waste and pack from around the upper well, the casing was broken at the nearest joint, separated and laid out for further study. Detailed notes on the waste profile and well condition were made. Below 1.5m, it was considered too dangerous to enter the excavation, due to the danger of collapse. Observations could therefore only be made from a secure harnessed position at the edge of the dig.

Figure 4.5. Trenching works and well excavation

Some details of pumping history and leachate level, since the installation of the pneumatic dewatering system (no earlier records are available), are given in Table 4.2.

	Lowest leachate level (mOD)	**Highest leachate level (mOD)**	**Average leachate level (mOD)**	**Initial drill depth (mOD)**	**Base depth before exhumation (mOD)**	**Volume pumped (approx) (m^3)**
716	1.90	9.76	4.80	1.20	1.77	920
730	0.97	8.63	5.87	0.70	1.66	375
734	0.67	8.63	5.80	0.43	0.93	422

Table 4.2. Well data for wells 716, 730 and 734, Phase 1, Rainham landfill between 10/05/00 and 6/12/01

During the excavation, the vertical profile along the length of the trench was carefully logged to construct an accurate cross-section of the landfill (e.g. Figure 4.6). The sections showed horizontally extensive layers of waste alternating with extensive bands of more soily material presumed to be intermediate cover. The soily material was in many places up to 2 m in depth, whilst the waste was not found to be more than 1 m deep at any location. The initial depth of the waste layers would probably have been significantly greater than this. Current operations at the landfill where waste is layered in lifts 2-3 m in depth suggest that compaction under loading and degradation has reduced the depth of these layers.

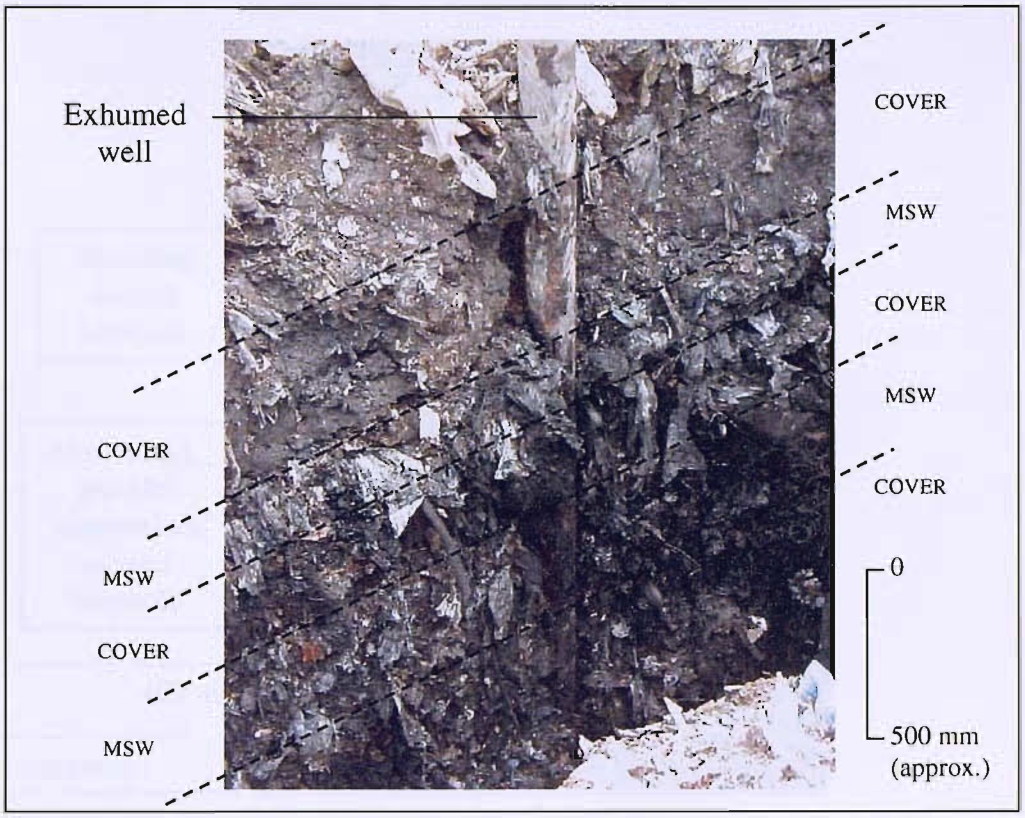

Figure 4.6. Alternating bands of MSW and cover material in lower stage of trench excavation and exhumation of well 716

4.3.1 Well bore observations

Annotated well logs of the three wells, with detailed observations of the waste, filter pack and condition of the casing, and slides taken during the exhumation works, can be found in Appendix B.

For each well, the well bore was fully intact to the base of the well, with no visible collapse into the borehole. This was unexpected in the upper section of the well, where no gravel pack had been emplaced to support the borehole wall (Figure 4.7). In the upper sections of the wells, smearing of sediments and waste pieces, pressed flat against the well bore, were observed. Parallel impressions were also visible around the well bore, and it is suggested

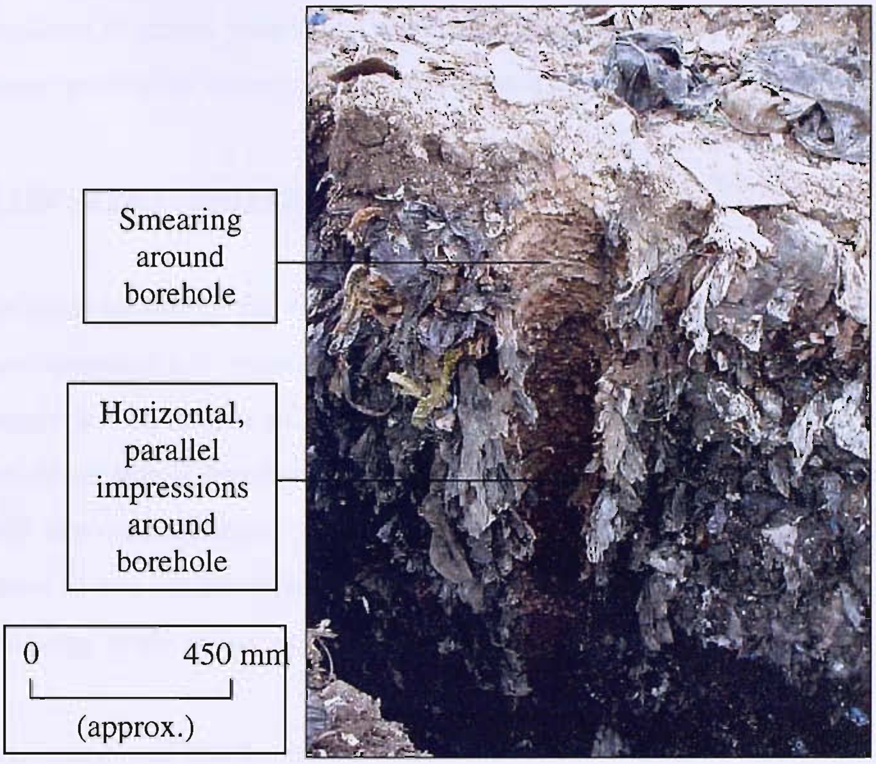

Figure 4.7 Open well bore showing possible smearing and horizontal impressions around borehole walls (well 730)

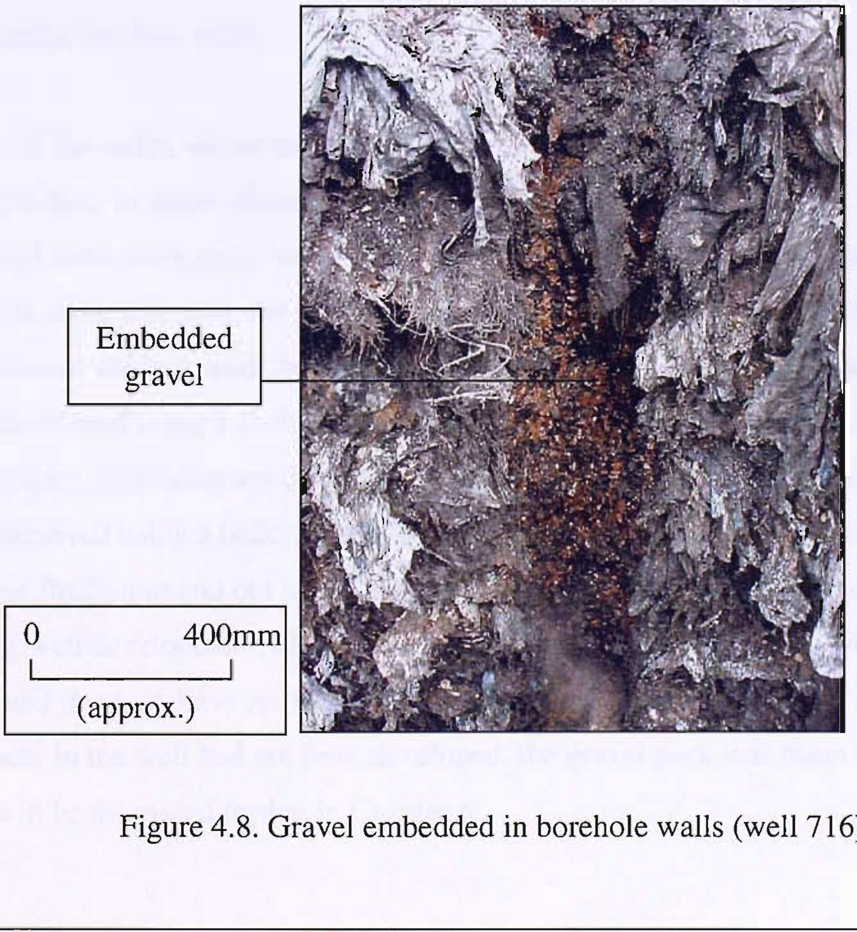

Figure 4.8. Gravel embedded in borehole walls (well 716)

that they may have been caused by the rotation of the drilling auger during installation. Impressions of gravel were often visible in the borehole walls and some pieces of gravel remained embedded in the side of the well as it was excavated (Figure 4.8).

4.3.2 Gravel pack observations

In the lower section of the wells, where a gravel pack was present, the gravel was neither cemented nor bound together by material that had entered the void matrix. When the borehole was excavated, the gravel pack collapsed into the open excavation. In places, some gravel remained embedded in the borehole walls, often where the adjacent landfill was predominantly MSW. Although measurements were made of the borehole diameter, it was not possible to conclude whether this material had been pushed into the surrounding waste or had adhered to the inside of the bore.

A wet, orange and black microbial slime was noted to cover much of the gravel pack for a depth of 0.5 m, at approximately 5.3 mOD in well 716. Descriptions of similar microbial clog material (for example, Nikolova, 2004) suggests that this may be an extra-cellular polysaccharide material from an iron oxidising bacterium. The material did not bind the gravel. The microbial slime was only present in the gravel pack above the average leachate table.

In two of the wells, where the pack was placed against waste, the gravel was clean and free of debris. In areas where the pack lay against a horizon of cover soils the gravel appeared to be more soily, and gravel was observed to be embedded in the borehole walls. In some horizons, the gravel was fully contaminated with soils (i.e. 100 % occlusion of voids, visual observation only) (Figure 4.9). These wells had previously been developed using a shell and surge-block operated from a cable percussive drilling rig (Chapter 6). During the development works, sediments from the base of the wells were removed using a bailer, the well backfilled with water / leachate and the shell used to surge fluids into and out of the well screen and pack to wash fines into the well. During well development, high velocity flows are created through the well screen and pack, and this may have resulted in the invasion of unconsolidated soils and waste into the pack. In the well had not been developed, the gravel pack was clean throughout. This will be discussed further in Chapter 6.

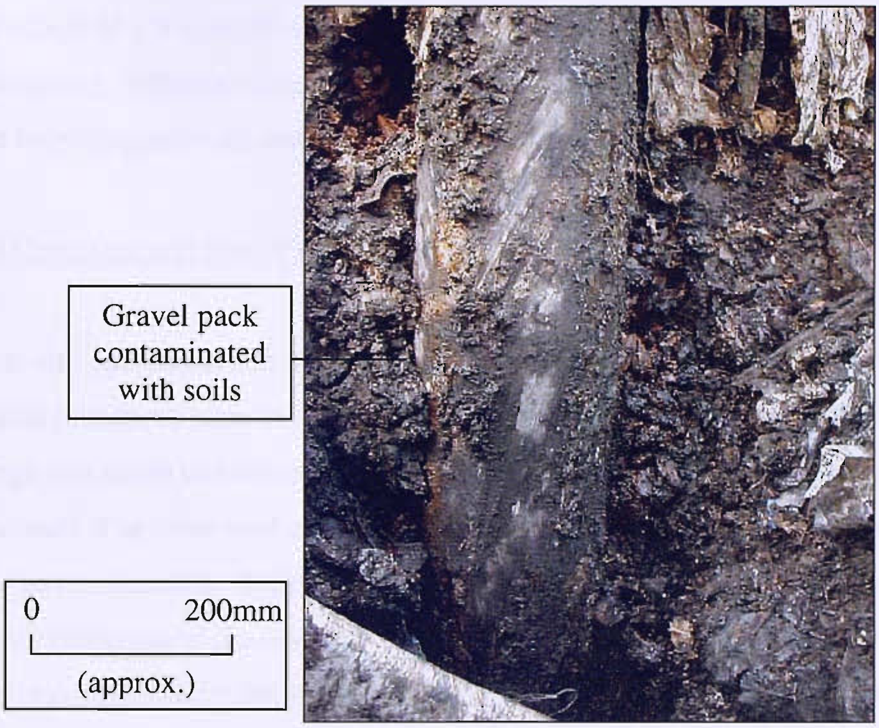

Figure 4.9. Gravel pack of well 716 contaminated with cover material

4.3.3 Well liner observations

The full well liner from two of the wells were removed from the boreholes and laid out on the surface so that more detailed observations could be made. The liner from the third well was damaged during the excavations and could not be removed cleanly from the landfill.

The casing from the upper sections of each well, from the gas zone above the permanent leachate table showed significant amounts of surface oxidation. In places, oxidation of the steel had resulted in layering and flaking on both the internal and external casing. In some areas this flaking was extensive around the entire circumference of the casing. In the screened section of the liner casing above the leachate level (approx. 6 m in length), slots were often fully closed by precipitates. Although flaking and corrosion were present around the whole casing circumference, they were more pronounced around the slots. There was less flaking with depth into the borehole.

The screened lengths of casing removed from the saturated zone showed virtually no corrosion both internally and externally.

An average of 1.8 m depth of sediment and pieces of waste were present within the base of the casing. Although free from encrustation and mineral precipitates, slots were often fully clogged with small pieces of waste and soil material.

4.3.4 Corrosion and loss of section

Due to site operations and the ongoing construction of the drainage trench, it was not possible to remove samples of the casing from the excavation for analysis. However, an attempt was made to estimate the degree of corrosion / oxidation throughout the length of the well. The recovered casing were cut into smaller sections of approximately 1 m to allow an examination of the casing's internal condition. Callipers were used to measure the wall thickness of the casing at each of the cut sections. Three measurements were taken at equal distance around the casing circumference. A wire brush was then used to remove any loose surface material down to clean metal and the measurements repeated as demonstrated in Figure 4.10. The measurements taken are presented in Tables 4.3 and 4.4 (full results are presented in Appendix B). Table 4.5 shows leachate level data from the wells.

Calculating the degree of surface oxidation was difficult, as corrosion, flaking and surface pitting were not uniform around the casing circumference. Also, new casing from the same manufacturer and of the same design, had variations in wall thickness of up to 4 mm. Nevertheless, it was assumed that the difference between the corroded wall thickness and the cleaned wall thickness, was an approximate indication as to the degree of surface oxidation.

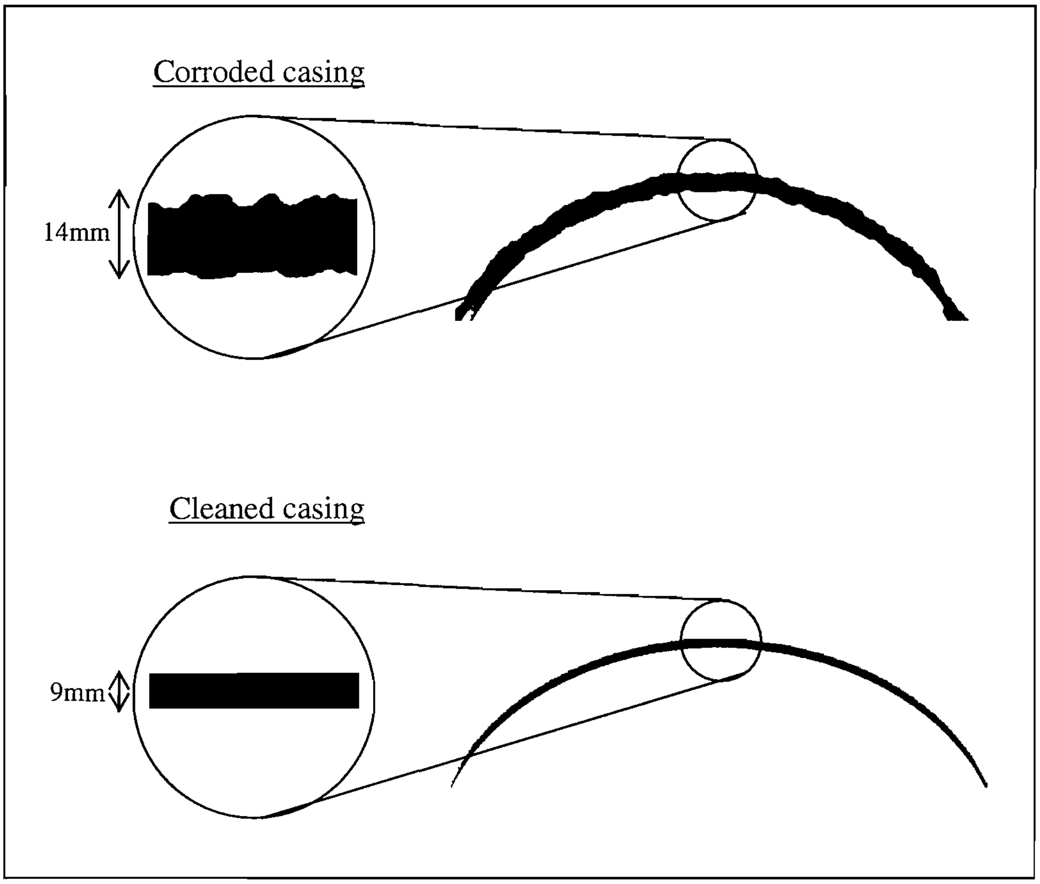

Figure 4.10. Measuring casing section thickness: corroded and after cleaning

Depth mBCT	Corroded Thickness (mm)	Cleaned Thickness (mm)	Difference	Extent of Corrosion
	Ave	Ave		
1.10	13.3	9.3	4.0	High
1.80	14.3	9.6	4.7	High
2.60	14	9.6	4.4	High
3.40	11.3	10.3	1.0	Low
4.16	14.3	9.6	4.7	High
4.96	12.3	9.3	3.0	Some
5.73	11.3	10.6	0.7	Low
6.51	10.6	10	0.6	Low

(mBCT = meters below casing top)

Table 4.3. Wall thickness of casing from well 716 (upper 6.5 m only)

Depth mBCT	Corroded Thickness (mm)	Cleaned Thickness (mm)	Difference	Extent of Corrosion
	Ave	Ave		
0.12	11.3	9.0	2.3	Some
1.91	14.7	8.7	6.0	High
3.07	14.3	10.0	4.3	High
5.07	12.0	11.3	0.7	Low
5.90	14.3	11.7	2.6	Some
8.00	11.3	9.7	1.6	Low
10.12	11.7	11.0	0.7	Low
12.07	11.7	10.7	1.0	Low
14.00	11.3	10.7	0.6	Low

Table 4.4. Wall thickness of casing from well 734

Well 716	**Lowest (18/02/98)**	**Highest (28/05/99)**	**Average**
mBCT	12.62	4.76	9.72
mOD	1.90	9.76	4.80
Well 734	**Lowest (07/11/01)**	**Highest (08/05/00)**	**Average**
mBCT	13.91	5.95	8.78
mOD	0.67	8.63	5.80

Table 4.5. Leachate level data for wells 716 and 734

As was observed in the CCTV surveys, it was the upper parts of the wells that had the highest level of corrosion, with between 7 and 6 mm reduction in section. In the lower parts of the well, within the saturated zone, little corrosion was noted, with a 1 – 2 mm change in wall thickness. The casing from each well showed a small decrease in wall thickness with depth.

4.4 Key findings from well surveys

- organic and inorganic encrustations are common in leachate wells, though will usually only be above the level of the leachate in the well, and will, therefore, not affect the performance of a the well.

- a well skin was observed in wells drilled using rotary barrel auger techniques. Smearing and compaction, and gravel pack embedded in the borehole walls were observed in three wells.

- total occlusion of the gravel pack with soils was noted in the wells that had previously been developed, though only where the gravel lay against a horizon of cover soil. Where the pack lay waste the gravel was clean and ran freely. Development may cause the invasion of material into the gravel pack.

4.5 Chapter Summary

The remote inspection by CCTV was a quick and relatively inexpensive means to obtain a visual record of the downhole construction and condition. It was difficult to get a good range of sample wells though, due to well access and site operations. A quota-based essentially random sampling strategy was used.

The downhole CCTV surveys have shown the potential for chemical precipitation in leachate wells. Of the wells surveyed, up to 80 % showed some degree of precipitate material occluding slots in the well screen. The degree of clogging varied from 0 to 100 %, where slots were completely closed by mineral precipitates or oxidation products.

In all wells where clogging was noted in the well screen above the leachate level, *below* the leachate level slots were generally clear and free of mineral deposits. Only in one of the wells surveyed were there encrustations around the well screen below the leachate level. It was not possible to determine how far into the well these deposits went owing to the opacity of the leachate. This is important: if wells are not clogging below the leachate table, then clogging may not be a significant mechanism in well deterioration.

The excavation of the deep dewatering trench gave the opportunity to examine three leachate extraction wells, their well pack and surrounding waste *in situ*, with only limited disturbance to the well and waste formation. Nine years after installation and following four years of continuous leachate extraction, significant ground settlement, further tipping and landscape restoration, the constructional integrity of each borehole was excellent. Possible smearing of the well bore and compaction of the waste in the borehole walls was observed. Although microbial deposits were encountered in the filter pack of one well, they were limited to a narrow horizon above the leachate table. In general, the pack was clean and uncemented throughout. There was, however, in two of the wells, evidence of physical clogging, especially where the pack lay against horizons of cover soils. These wells had previously been developed and this may account for the differences (invasion of the pack was not observed in the well that had not been developed).

The well screens removed during the exhumation showed much corrosion in the upper sections of the wells, above the permanent leachate table, with precipitates often fully closing slots. No corrosion was observed below the leachate table. In areas of highest corrosion, the reduction in wall thickness between cleaned and corroded casing was between 6 and 7 mm.

Chapter 5

Drilling methods and hydrogeological testing of new wells

5.1 Introduction to Chapter

Rotary barrel auger drilling was used to install 60 percent of the wells examined in the vertical well database. This technique has been described as being the most suitable for installing wells - through most materials - in a landfill (Burrows, 1998). However, as the auger rotates into the waste, ground waste and soils may be smeared and compacted around the borehole sides, leaving a skin of low permeability material around the circumference of the borehole (e.g. Driscoll, 1987, Nielsen, 1991, Barash *et al.*, 2005). A well skin was observed in the wells exhumed at the Rainham landfill, where smearing of ground waste and cover soils around the inner walls of the borehole was evident, and in places pieces of waste were flattened against the borehole walls (Section 4.3). This may have been caused by the drilling auger. Losses through the well skin will result in greater drawdown within the well (e.g. Barrash, 2005). The greater the zone of disturbance, the more significant the well loss. Also, ground waste and soils from the sides of the well may be mobilised during pumping, resulting in the clogging of the filter pack and screen, and material entering the well may lead to premature pump wear.

Continuous flight auger drilling, accounted for 32 percent of the known drilling techniques in the database. In field trials, Burrows (1998), suggested that the technique was not suitable for some waste types, because the flight could be easily deflected off large objects and could not penetrate all materials. However, with no rotating barrel, the extent of compaction and smearing in a well installed using flight auger methods may be much reduced.

Minimising well skin and developing of wells (to remove or reduce the effects), is a critical part of ground water well installation, yet the extent and effect of well skin and the use of different drilling methods has not previously been examined in landfill. To investigate the effect of drilling technique on leachate well performance, a trial was undertaken at the Ockendon Landfill, Essex and the Westbury Landfill, Wiltshire. The aims of the drilling trial were:

- to determine the applicability of different drilling methods for installing wells in landfill, and
- to evaluate the difference in performance between wells installed using different drilling techniques.

5.2 Landfill drilling trial

The drilling trial area is situated on the restored Area 1 region of the Ockendon Landfill. The landfill was a former site of clay extraction and is now restored following tipping of MSW to a thickness of approximately 35 m.

Three leachate extraction wells were drilled, each using a different technique: rotary barrel auger, rotary open hole and solid stem continuous flight auger. The wells were drilled to approximately 30 m in depth. To allow comparisons of the pumping between the wells, it was necessary to drill the boreholes in close proximity to each other to minimise the effects of waste heterogeneity on the well yield. The wells were installed at 5 m centres. Each well would be pumped in turn, with full recovery of the pumping well and all observation wells before a different well was pumped.

Nine monitoring points were drilled at distances between 3 m and 20 m radially from the extraction wells, each with two piezometers installed at different levels within the saturated waste (at the base of the borehole and in the upper waste at the top of the leachate table). A multi-level magnetic extensometer was installed in close proximity to the wells to monitor waste settlements during pumping.

Where possible the waste arising from the three well boreholes and nine piezometer boreholes was described and classified using a framework detailed by Board *et al.* (2001). The waste from each borehole was similar, comprised dominantly of damp to moist, poorly decomposed MSW refuse. Some inert material (including brick, rubble and metal), was encountered in the upper 14 m of the waste, accounting for 10 to 20 % of the material recovered (in some horizons up to 40 %). Approximately the lowest 10 m of waste was saturated. A plan of the trial well locations is shown in Figure 5.1.

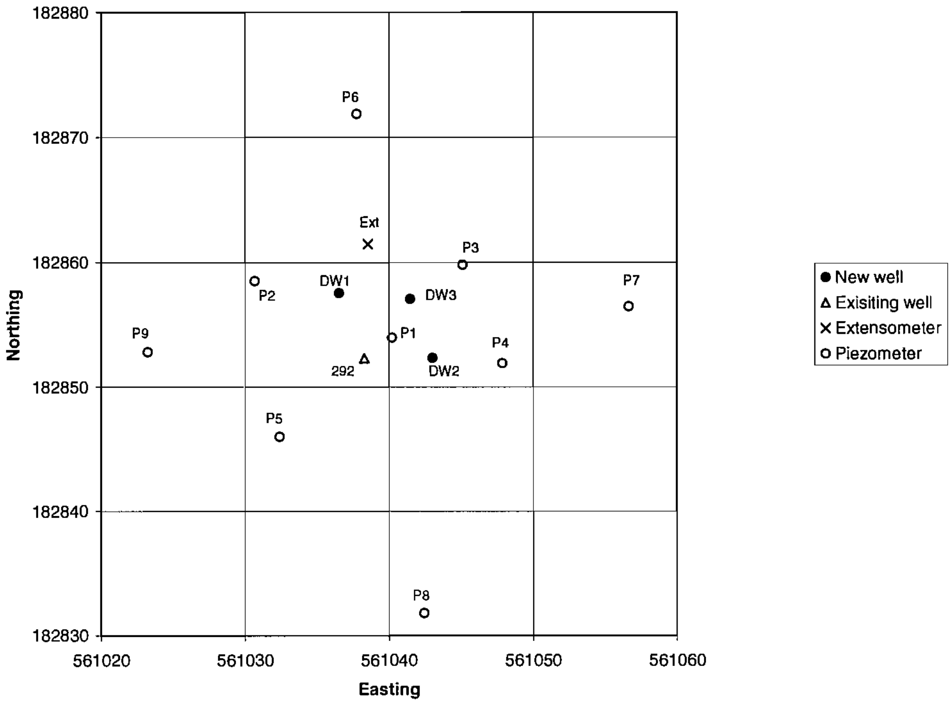

Figure 5.1. Location of new wells and piezometers, Ockendon landfill

5.2.1 Drilling methods

Three different methods were trialed to drill and install the new wells. The methods and observations made from each are described below.

Barrel auger method - a vertical hole is cut into the waste using a rotating, hollow auger. The auger is rotated into the ground until it is full, the drill string is withdrawn back to the surface and the material held within removed. The process is then repeated, and the borehole progresses to depth in cored sections each the length of the auger. As the well advances and the maximum extent of a drilling rod is reached, a second (or third, fourth etc.) rod is fitted. This second rod must then be removed before the auger can be brought to the surface and emptied.

At Ockendon, as each full auger was returned to the surface, the profile of the waste was logged. The depth of the waste horizons were measured using either a weighted tape lowered into the borehole from the surface, or calculated from the length of the drilling rods used. Although the waste core inside the auger may have been compacted somewhat by the drilling process, the waste was relatively undisturbed and usually represented to within 0.5 m the waste profile.

For installing boreholes in waste, this method has the advantages of:

- cutting teeth that can penetrate most obstacles encountered,
- removing waste from the borehole as it is drilled,
- creating a vertical borehole for its full depth with relatively clean sides (i.e. little waste protruding from the sides of the borehole),
- allowing the logging of waste.

The disadvantages of this method are that:

- some waste will be finely ground by the action of the cutting teeth,
- the rotating barrel can smear the waste forming the sides of the borehole, possibly reducing permeability,
- unless a clack valve or fan auger is fitted to the barrel, it can be difficult to remove saturated waste from the borehole as the waste can fall out of the barrel.

Rotary open hole method - the rotary open hole drilling method utilises a tricone to cut through the formation, and a drag bit to ream the borehole to the required diameter. Cuttings are returned up the borehole by a compressed air / mist (water) flush supplied through the drilling rods from a rotary joint on the drilling head. The water mist also serves to cool the tricone bit as it cuts.

The advantages of this method are:

- reduced waste returns from the borehole, which may be important if hazardous materials are present,
- potentially quicker drilling as the drill string does not have to be removed from the borehole until the base of the well is reached.

Disadvantages of this method are:

- the borehole is created by cutting and pushing the waste into the borehole walls rather than extracting the waste. This may lead to compaction and smearing of the waste material which may result in a reduction in the permeability of the waste around the borehole,

- logging of the waste cannot be carried out,
- the contamination of the ground from air-flushing drilling returns.

Solid stem flight auger - a continuous flight auger (known also as a cork-screw auger) consists of a plugged tubular steel centre shaft or axle, around which is welded a continuous steel strip in the form of a helix. Each individual auger or 'flight' is rotated into the ground, before a second is attached. When connected, the helix is continuous across the sections and throughout the depth of the borehole. An auger drill head (with tungsten carbide steel cutting teeth) is attached to the bottom auger flight. The tip of the flight auger is fitted with hinged tines to assist the auger in penetrating the formation. As the auger is rotated into the waste, the drilling head will cut a vertical shaft through the waste. As the auger rotates, waste pieces will be carried along the axle of the auger to the surface along the rotating helix. As noted by Burrows (1998), however, the precision of logging of waste recovered from flight augers is limited. A proportion of the waste penetrated will be forced into the walls of the borehole and will therefore be unavailable for examination. In addition, the recovered material can often be disturbed and mixed by the rotation of the bit. When the auger reached saturated waste, partial loss of the sample was common.

Advantages of this method are that:

- waste is removed from the borehole as it is drilled,
- the waste is not ground by the action of the flight auger, it is splintered or broken, resulting in larger fragments of material arising from the borehole,
- large diameter holes can be drilled using this method,
- manual handling of waste can be eliminated by using a drill bucket to collect arisings.

Disadvantages of the method are that:

- the flight auger can be deflected from the vertical by obstructions,
- the flight auger does not penetrate obstructions easily,
- some waste may be forced into the formation.

Well DW1 was drilled using the rotary open-hole method. Toward the base of the borehole, the drill string became stuck and required considerable force to free it. Because of the potential for the drill string to be damaged or lost in the waste formation, it was decided to complete the borehole with a 200 mm diameter barrel auger. Although the borehole was drilled to a depth of 29 mBGL, the well liner could only be installed to a depth of 27.80 mBGL. The inability to install the liner to the correct depth is considered to have been due to the ragged finish of the borehole and the small clearance between the casing and the 200 mm diameter borehole over the bottom 7.2 m. As the liner was installed into the borehole, waste may have been pushed down the borehole ahead of the liner, until the last metre of the borehole was blocked by compacted waste.

The three boreholes were completed with a 160 mm diameter steel well liner with punched 5 mm × 25 mm vertical slots giving an open area of 25 percent. A filter pack formed of 10-20 mm washed gravel was placed in the annulus between the casing and borehole in wells DW2 and DW3. The gravel size was chosen on the basis of the screen slot size and without prior knowledge about the waste PSD. Because of the narrow annulus between the well screen and borehole, well DW1 was installed without a gravel pack. The void between the casing and the borehole was backfilled using the waste arisings. The wells were not developed following installation.

The borehole drilling and completion is summarised in Table 5.1. After the wells were installed, a series of hydrogeological pumping tests were carried out to investigate differences in performance between the different designs. The test methods, analysis and results can be found in Section 5.3.

Well No.	Drilling Method	Depth of Well (mBGL)	Screen Length (m)	Filter Pack
DW1	Rotary open hole	27.80	9	No
DW2	Barrel auger	29.00	9	10 – 20 mm
DW3	Continuous flight auger	29.00	9	10 – 20 mm

Table 5.1. Well completion details

5.2.2 Hammer-driven fully-cased drilling

Morin *et al.*, (1988), describe a statistical evaluation of the formation disturbance (well skin) in fifteen wells, installed using three different drilling methods: rotary open hole with drilling mud, continuous flight auger and hammer-driven, fully-cased. The wells were installed in very loose, unconsolidated sands and gravels. The degree of formation disturbance was measured using down-well geophysical probes. Morin *et al.* (1988), conclude that the greatest degree of disturbance (measured as a reduction in porosity) was in the wells installed using the flight auger method. The hammer-driven fully cased boreholes, showed the least disturbance to the surrounding formation.

Hammer-driven, fully-cased borehole drilling had not been previously tested in landfill. Discussions with plant operators suggested that although the method may be suitable for leachate wells, the time and costs of installing a single deep well for experimental purposes would be prohibitive. Rather than installing a fourth deep well at the Ockendon landfill, a shallower well was drilled at a different landfill with similar waste characteristics (waste type and age) and saturated depth of waste (~ 20m). Although a direct comparison between the wells installed at the two sites would not be possible, a qualitative assessment of the suitability of the drilling method could be made.

The hammer-driven drilling rig uses a rotating pneumatic hammer to create a borehole in the formation. Temporary casing, to hold the borehole open, is attached to the hammer and pulled down through the formation as the hammer progresses. When the end of the drill rod connecting the hammer to the drilling head is reached, another is attached. This is repeated until the drilling head and the temporary casing have reached the required depth. Cuttings are returned up the borehole by a compressed air / mist flush supplied through the drilling rods. Because the drilling method displaces material into the borehole walls rather than to bore an opening, only a limited amount of material is expected to enter the casing.

The trial well was installed in the NW Area of the Westbury landfill. The maximum drill depth, estimated from the depth of adjacent wells, was set at 20 mBGL. The Westbury landfill is described in Section 7.2.

Although the drilling method was slow, taking almost twice the time as the previous methods, the borehole was successfully drilled and a clean installation made. However, it was not possible to complete the well because the temporary casing (used to hold the bore open) could not be pulled from the borehole. It is suspected that the frictional grip of the waste around the temporary casing was such that even at its maximum operating lift, the drilling rig could not pull the casing from the ground. Attempts to recover the casing were unsuccessful and the borehole was abandoned.

The advantages of this method are:

- reduced waste returns from the borehole, which may be important if hazardous materials are present,
- The technique allows boreholes to be drilled in materials that might otherwise collapse, with few arisings and little contamination,
- or in areas where a high gas output could limit conventional drilling methods (the cased well prevented gas entering the borehole).

The disadvantages of this method are:

- slow in comparison to more commonly used methods (e.g. barrel auger, flight auger),
- it may only be suitable for shallow wells (< 20 m depth) due to the problem of removing the temporary casing from the borehole.

5.3 Hydrogeological testing of new wells

The use of pumping tests to determine the performance and efficiency of a groundwater well and the properties of its surrounding aquifer is an established practice used in the water abstraction industry. Pumping tests can be divided into two categories; steady state pumping tests, in which a well is pumped at a constant flow rate until equilibrium is achieved in observation wells; and transient state testing in which water level falls in observation wells are measured over time. Procedures for carrying out pumping tests are described in standards such as BS 6316:1992. A variety of methods have been developed to analyse data generated by the pump testing of wells. These often incorporate a number of simplified assumptions regarding the properties of both the well and aquifer. Investigations by Burrows (1998), have demonstrated the applicability of groundwater test methods for pumping test analysis in landfill. Practical difficulties such as maintaining consistent flow rates over an extended period of time and the lack of appropriate monitoring wells may restrict the extent of analysis. Nevertheless, the results gained from pumping tests are generally accepted in the groundwater industry as the best available method of investigating aquifer properties and well efficiency, and will therefore be used in this thesis to assess the performance of landfill wells.

To evaluate the performance of the new wells installed at Ockendon, a programme of short term hydrogeological pumping tests was carried out in each of the wells. These were to include constant discharge tests and short-term step-drawdown tests (completed). During the course of the pumping tests, a subterranean landfill fire believed to have been caused by over-extraction from a surrounding landfill gas system and the failure of the wells' bentonite seals, destroyed much of the monitoring infrastructure and two of the extraction wells. At the landfill operator's request, the test programme was halted and the remaining wells and piezometers abandoned and grouted to surface.

5.3.1 Step drawdown tests

Short term step drawdown tests were carried out to compare hydraulic performance and efficiency. A step-drawdown test is a short-term test used to establish the yield-drawdown relationship of a well, and thereby define and distinguish between aquifer losses and well losses. The step-drawdown test can be used to evaluate a well's performance, quantifying the well loss component of drawdown (i.e. head losses within the bore-hole, filter pack and well screen), and the formation losses.

A three-step drawdown test was carried out in each of the three new well installations, following test procedures outlined in BS 6316 (1992) for step drawdown tests. Changes to the standard test procedures included running only three steps, instead of the recommended four, due to the restrictions of site working hours. An electric submersible pump with a capacity of 120 m^3/day at 31 m head was used for each test. Flow rates were controlled manually using a ball-valve. The duration of each step was 90 minutes for well DW2, 100 minutes for well DW1 and 110 minutes for well DW3.

During each step, the drawdown in the testing well and all surrounding observation wells was monitored using a dip-meter and automatic pressure transducers. After the pump was switched off, the wells were monitored during recovery for at least 24 hours.

Table 5.2 summarises discharge and drawdown data for each well test. Time / drawdown (Sw) for each test is shown in Figure 5.2. Full results from the step drawdown tests and analysis can be found in Appendix C.

	DW1 Rotary open hole		**DW2 Rotary barrel auger**		**DW3 Flight auger**	
	Q m^3/hour	**Sw (m)**	**Q m^3/hour**	**Sw (m)**	**Q m^3/hour**	**Sw (m)**
Step 1	0.37	0.24 @ 100 min	1.10	0.30 @ 91 min	0.52	0.36 @ 100 min
Step 2	1.36	1.17 @ 200 min	1.94	0.68 @ 181 min	1.51	1.24 @ 200 min
Step 3	2.83	2.10 @ 255 min	2.65	1.08 @ 270 min	2.51	2.16 @ 300 min

Table 5.2. Drawdown and flow rates for each step drawdown test, Ockendon drilling trial

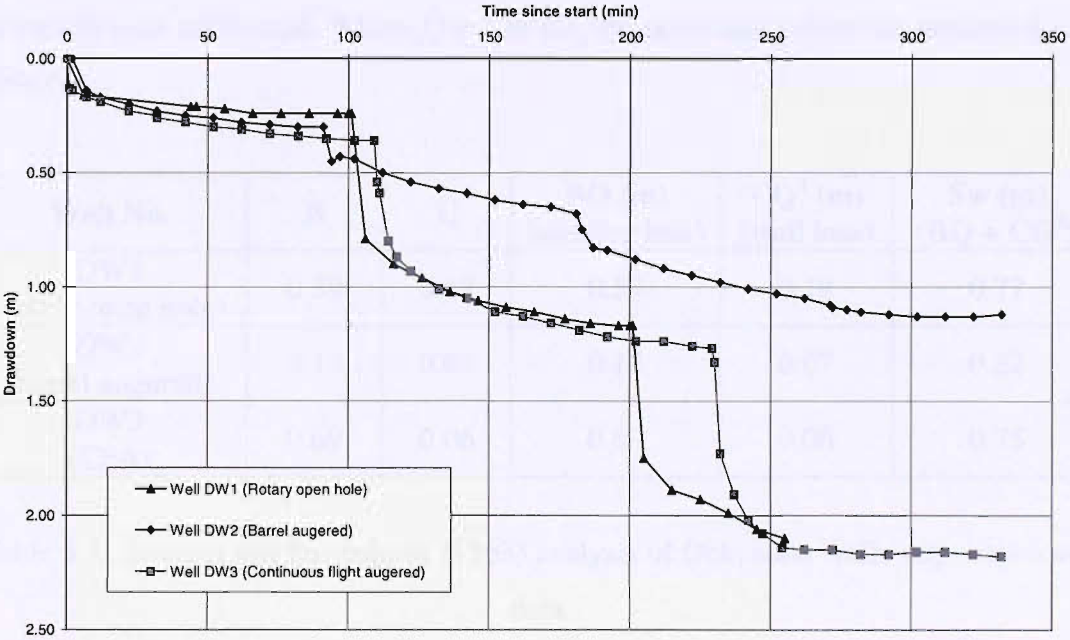

Figure 5.2. Drawdown (Sw) during step-drawdown tests, Ockendon drilling trial

The Jacob (1947, in Kruesman and De Ridder, 1984) equation, can be used to explain drawdown in a pumped well:

$$Sw = BQ + CQ^2$$

Where:

Sw = drawdown,
B = the linear head loss coefficient,
C = the non-linear head loss coefficient,
Q = discharge rate.

BQ represents the aquifer loss and CQ^2 the well loss component of drawdown. The aquifer loss is a function of the aquifer characteristics and is, therefore, not affected by well design. The well loss component of drawdown is the drawdown caused by energy losses due to turbulent flow around and inside the well. Well loss is a function of the well construction and damage caused through installation (well skin). Using the Hantush and Bierschenk (1963, in Krussman and de Ridder, 1994) method of step-test analysis, the values of B and C, and the well loss and aquifer loss components of drawdown were calculated. Where Q = 1 m^3/hr, the calculated values are presented in Table 5.3.

Well No.	**B**	**C**	**BQ (m) (aquifer loss)**	**CQ^2 (m) (well loss)**	**Sw (m) ($BQ + CQ^2$)**
DW1 (rotary open hole)	0.59	0.18	0.59	0.18	0.77
DW2 (barrel augured)	0.15	0.07	0.15	0.07	0.22
DW3 (CFA)	0.69	0.06	0.69	0.06	0.75

Table 5.3. Hantush and Bierschenk (1963) analysis of Ockendon wells step drawdown data

The results of the step drawdown tests show the aquifer loss calculated for each well to be similar, though there is a slightly smaller component of linear head loss (B) in well DW2. This indicates, that despite the close spacing of the wells, some heterogeneity exists in the waste, though the difference is small. The calculated well losses, again show little difference between the wells, though well DW1 (the well drilled using rotary open-hole methods) has a slightly larger component of non-linear head losses (C). Significantly, the aquifer loss part of the drawdown is an order of magnitude greater than the wells loss.

5.3.2 Analysis of results

The step-test analysis has demonstrated, that even at 5 m centres, the aquifer loss component of drawdown was different between wells, implying heterogeneity in the waste across the test area. Burrows (1998), examined pumping test data from a number of landfill sites, and noted that where the hydraulic conductivity of the landfilled material varied laterally from the pumped well, where hydraulic barriers existed, or where a preferential flow direction was present, the cone of depression was offset, oval or of irregular form in plan view.

Well DW1, was drilled using open-hole methods with a drag-bit and reamer, and installed without a filter pack. During drilling, in comparison to the barrel augured well and the flight augured well, very little material was returned to the surface, and was instead pushed into the borehole walls. This would have created a zone of compacted waste around the borehole, with a lower permeability than the waste outside the zone, resulting in greater well losses during pumping. Milling of the waste and the smearing of soils during the drilling, could also plug voids in the waste around the borehole, reducing permeability further.

The pumping tests in the barrel augured well, and that installed with the flight-auger shown no difference in performance. The wells were installed with the same well screen and filter pack, and to the same depth. The pumping tests, therefore, represent analysis of the well skin, rather than differences in construction. The test results show no difference between the two techniques, and that if a well skin had been created, it was similar in each well.

Table 5.4 compares the estimated well loss (CQ^2) for the three wells for the range of daily flow rates given in Table 2.1 (0.15 to 59 m3/day, average 8.5 m^3/day). Even at the highest flow rates reported for landfill wells (~59 m^3/day), losses are minimal, and the difference between installation types insignificant.

	CQ^2 (m)		
Q (m^3/day)	DW1	DW2	DW3
0.15	<0.01	0.02	1.11
8.5	<0.01	0.01	0.43
59.0	<0.01	0.01	0.35

Table 5.4. Calculated well loss for a range a flow rates of typical landfill wells

In all wells, the aquifer loss component of drawdown is significantly greater than the well loss component (by an order of magnitude). The controlling factor in leachate well efficiency is, therefore, the hydraulic property of the waste in the zone of influence around the well, rather than the specification of the borehole and well installation itself.

The trials have shown, that for drilling new wells in landfill, the choice of drilling method is not significant, though if the well is to be logged, then barrel auger drilling is the best method. Rotary open-hole drilling is common in consolidated natural formations. In landfill, the method may not be suitable for deep wells owing to the collapse of the waste into the well during installation. At Ockendon, the well had to be completed with a barrel auger to reach depth.

Table 5.5 compares the range of well parameters noted in the database with the specification of the new wells. Although the drilling trials discussed only include three wells at one site, the new well installations are comparable (in terms of waste type, saturated depth and installation) with other leachate wells. The trials are therefore considered representative, and the implications transferable to other landfill sites. The performance of individual wells may differ between different landfills though, because of differences in saturated depth, age of waste and compaction.

	Data-base	**Trial wells**
Waste type	MSW	MSW
Borehole depth	7-36 m (ave. 20 m)	29 m
Saturated depth	4-22 m (ave. 12 m)	12 m
Drilling method	60 % Rotary / 30 % CFA	Rotary / CFA / open hole
Screen type	Steel (66 %)	Steel
Screen slots	(steel screens) 10 × 100 mm	5 x 25 mm
Pack type	5-40 mm (43 % 20 mm)	20 mm
Ave. yield	0.15-59 m^3day (ave. 8.5 m^3/day)	Tested at 10-65 m^3/day

Table 5.5. Specification of new well installations in comparison to typical leachate wells

5.4 Chapter summary

The drilling trial at the Ockendon landfill was carried out to investigate the drilling of boreholes through waste using three different methods: the barrel auger, solid stem flight auger and a rotary open hole method. Each method was found to have advantages and disadvantages in terms of installation. The rotary barrel auger drilling technique was capable of penetrating most waste types. The process of removing each core from the landfill to progress the borehole allowed the accurate logging of the waste, but did increase the installation time. It was difficult to clean out the base of the borehole when drilling through saturated waste. Continuous flight auger drilling methods were more rapid, though accurate logging of the waste was not possible. The flight stem was often deflected from vertical by large waste objects. Rotary open-hole drilling using a tri-cone and drag bit was also rapid, though due to difficulties in recovering the drill stem at depth, the well was finished using barrel auger methods. Logging of the waste was not possible using this method.

A fourth drilling method – hammer driven, fully-cased - was trialed at the Westbury landfill. This drilling method had not previously been trialed in landfill, and although the well was drilled to depth, difficulties in removing the temporary casing led to the borehole being abandoned. For these reasons, the technique may not be viable for deep wells and its suitability for landfill well drilling is yet to be proved.

Hydrogeological pumping tests have been used to characterise and compare the new installations. Short-term step-drawdown tests were carried out on the three wells. The results of the pumping test were analysed using the Hantush and Bierschenk (1963) methods. The aquifer loss component of drawdown was similar in each well, though there was a slightly smaller component of linear head loss in well DW2. The calculated well losses show little difference between the wells, though the well drilled using rotary open-hole methods, has a slightly larger component of non-linear head loss. This may be attributed to smearing of the well bore and compaction of the waste by the action of the drag-bit and reamer during drilling. The wells installed using barrel auger and flight-auger techniques were comparable in terms of performance.

For drilling wells in landfill, rotary barrel auger or continuous flight auger methods are recommended. If the borehole profile is to be logged, then barrel-auger methods are the more accurate.

When pumping from a leachate well, the aquifer loss component of drawdown will be significantly greater than the well loss component. The efficiency of a leachate well will, therefore, be a function of the local waste properties, rather than the drilling method and installation of the well itself.

Chapter 6
Well development

6.1 Introduction to chapter

The purpose of well development is to remove the well skin that may be formed during the drilling and installation of a well, and to aid on the remediation of failing wells by cleaning deposited material from the well liner and filter pack. The aim is to alter the physical characteristics of the aquifer near the borehole in order to allow leachate to flow more freely toward the well, by removing fine particulate matter from along the well screen-aquifer/well screen-filter pack contact and some distance into the waste formation. Traditionally, in the groundwater well industry, well development is carried out soon after installation and before pumping commences. Site records, discussed in Chapter 2, suggest that newly installed wells in landfill are rarely, if ever, developed directly after a new well has been installed. The deposition of particulate matter in the well bore over time is, however, common, and accumulations of material several metres in depth are not unusual. As well as the premature wear to pumping equipment, the deposits prevent pumps being installed to the base of the well and reduce the effective drawdown.

A well development trial was initiated to determine the applicability and effectiveness of well development in commissioning and remediating landfill wells. The trial was performed at two sites: the Rainham landfill, Essex, where a well field was developed using two different techniques, and the Westbury landfill, Wiltshire where existing pumped wells were developed and compared (in terms of performance and the ingress of sediments) to newly installed unpumped wells.

Hydrogeological pumping tests and long term pumping data were used to quantify changes in performance, and assess the suitability of well development in landfill. The development techniques and some results will be presented for each trial, and then the results and analysis will be discussed collectively. More detailed results and analysis can be found in Appendix D.

6.2 Well development trial 1

The first development trial was carried out at the Rainham landfill, Essex. 21 wells in the Phase 1 area of the landfill were selected for the trial. The locations of the wells are shown in Figure 6.1. The well field had been installed in 1995, using rotary barrel auger drilling techniques. A limited amount of leachate pumping had taken place before the development trial, though not all wells were pumped and yields were low and intermittent (due to the limitations of the pumping system, not the capacity of the wells).

The well field was developed in two stages; initially four wells were selected to test the chosen development technique (bailing and surging) for suitability and to collect samples of sediment for analysis. Following this first stage, approximately half the well field was developed using bailing and surging techniques, and all remaining wells developed using overpumping techniques.

6.2.1 Stage 1 methods

Four wells were developed using surge and bailing development methods.

The aims of the trial were to:

- clean the wells of sediment and waste that had collected in the well bore, to allow pump installation to the base of the wells,
- collect samples of material from the wells for particle size distribution (PSD) analysis to aid future well screen design,
- assess the suitability of surge and bail development techniques in landfill,
- compare the performance of the developed wells with undeveloped wells.

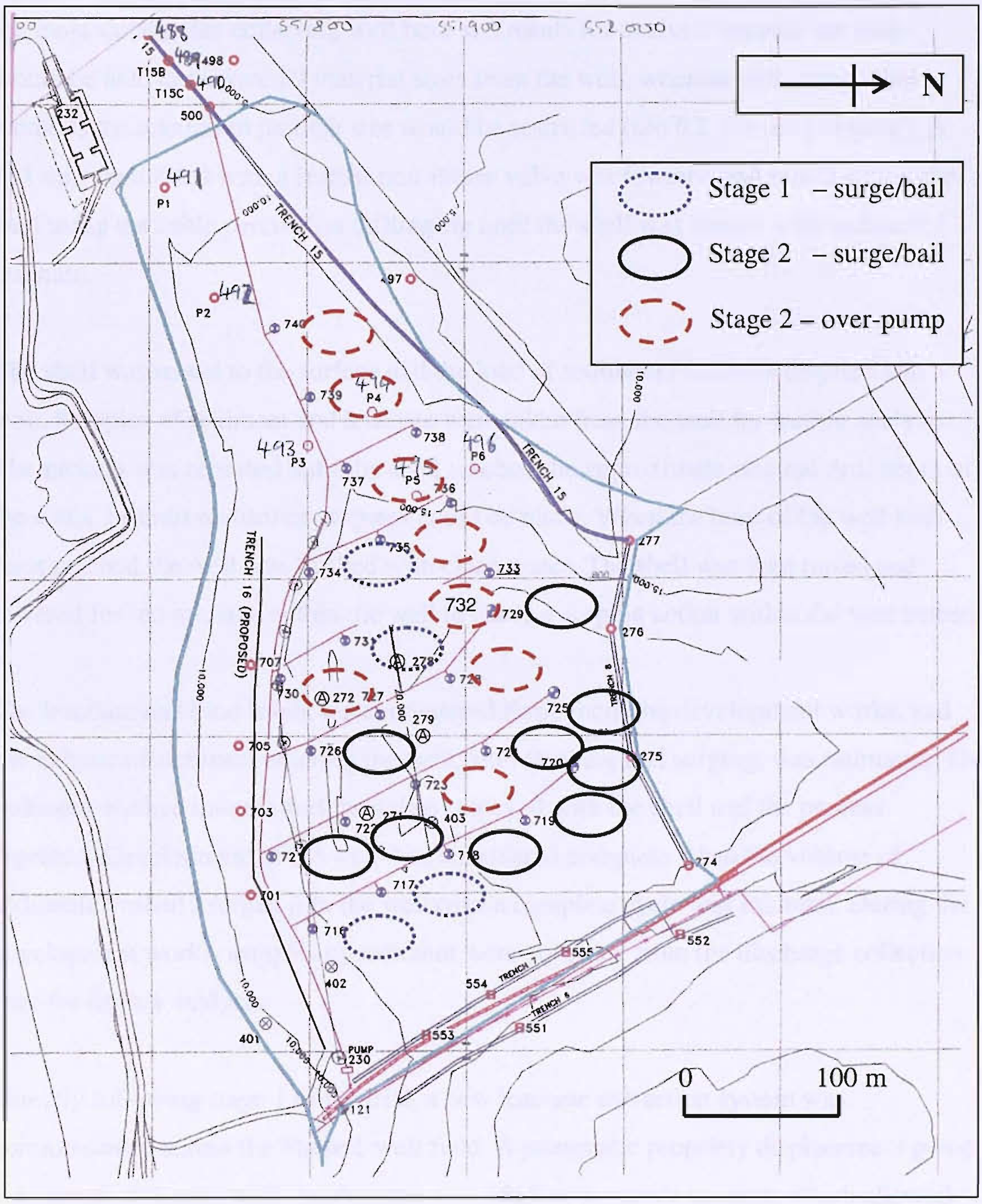

Figure 6.1. Location of developed wells, Phase 1, Rainham landfill

Development was carried out using a cable percussion drilling rig with a shell for the lifting and surging of sediment / leachate. This method of development was considered the most suitable for collecting well bore sediments for analysis because the bailer would be able to remove all material sizes from the well, whereas with some other methods the maximum particle size would be restricted (see 6.2.2, over-pumping). A 114 mm shell fitted with a leather non-return valve was lowered and raised within the well using the cable percussion drilling rig until the shell was loaded with sediment / leachate.

The shell was raised to the surface and the load of sediment / leachate emptied into a tank. Samples of sediment and leachate were taken from the tank for further analysis. The process was repeated until the shell reached the approximate original drill depth of the wells, or until no further progress could be made. When the base of the well had been reached the well was flushed with clean water. The shell was then raised and lowered for ten minutes within the well to cause a surging action within the well screen.

The leachate and base levels were monitored throughout the development works, and the volume of sediment entering the well, after flushing and surging, was estimated. The sediment washed into the well was then removed with the shell and the process repeated. Development of the well was considered complete when the volume of sediment washed / surged into the well over a complete cycle was minimal. During the development works, samples of sediment were collected from the discharge collection tank for further analysis.

Directly following stage 1 of the trial, a new leachate extraction system was commissioned across the Phase 1 well field. A pneumatic propriety displacement pump was installed in each well. Each pump was fitted with a cycle counter, which allowed the yield from individual wells to be logged over time. Well yields, leachate levels and bases levels within the wells were monitored for approximately 12 months.

6.2.2 Stage 2 methods

Approximately twelve months after the initial development trial, a further nine wells were developed using the bailer / surging technique. These wells were selected for their accessibility to the development plant (a cable percussive drilling rig). In addition to the these nine wells, three of the four wells developed previously in Stage 1 were redeveloped. This was because the bases of these wells had risen as a result of sediment ingress during the twelve months following the initial development programme. Also, it was thought that a number of stages of development may be necessary to maximise the effects. The development method was the same for that used in Stage 1 – a shell operated by a cable percussive drilling rig. A 152 mm bailer was used instead of the 114 mm bailer used previously. It was considered that the large diameter bailer would remove more sediment and pick up larger objects, whilst at the same time surging leachate within the well more effectively. Each well was bailed / surged for approximately three hours. Sediments collected from the wells were deposited in a tank for disposal, though no sediment samples were taken for analysis.

For the remaining eight wells, an overpumping development technique was used. Basal sediments were first agitated using a narrow pipe, rapidly raised and lowered by hand from the well head. The suspended sediments were then pumped from the well using a large capacity (high yield) pneumatic displacement pump. Overpumping continued until no further sediments could be removed from the well (approximately four hours per well) and no fresh sediments were entering the well during pumping. To backwash the wells, water was added or leachate was pumped from adjacent wells. The maximum particle size of the material that could be removed through the pump was restricted to the diameter of the filter openings on the pump inlet (approximately 2 - 4 mm).

Following development, wells recharged for between 24 and 48 hours before pumps were reinstalled and pumping recommenced.

Well depths following each stage of development are presented in Table 6.1.

Stage	Well No.	Method	Well base before (mOD)	Well base after (mOD)	Change in depth (m)
1	716	114 mm bailer	3.05	0.75	2.30
	717	114 mm bailer	4.03	0.63	3.40
	731	114 mm bailer	3.93	1.53	2.40
	734	114 mm bailer	0.53	-0.05	0.58
2	717*	152 mm bailer	2.39	-0.12	2.51
	718	152 mm bailer	2.97	-1.36	4.33
	719	152 mm bailer	0.76	-0.73	1.49
	720	152 mm bailer	1.85	0.41	1.44
	721	152 mm bailer	2.26	0.24	2.02
	722	152 mm bailer	1.53	1.01	0.52
	724	152 mm bailer	2.26	0.72	1.54
	725	152 mm bailer	6.12	2.52	3.60
	726	152 mm bailer	2.27	-0.55	2.82
	729	152 mm bailer	1.04	-0.73	1.77
	731*	152 mm bailer	2.11	-0.11	2.22
	734*	152 mm bailer	0.67	-0.05	0.72
	723	Over pump	2.34	1.64	0.70
	727	Over pump	2.09	0.72	1.37
	728	Over pump	1.34	-0.06	1.40
	732	Over pump	4.89	3.17	1.72
	735	Over pump	1.94	0.44	1.50
	737	Over pump	0.81	-0.24	1.05
	739	Over pump	1.55	0.45	1.10
	740	Over pump	1.81	0.41	1.40

* wells developed for a second time

Table 6.1 Results of each development stage

6.2.3 Stage 1 results – well performance

Table 6.2 shows average daily well yields, from four developed wells and the other 17 wells in the well field over 300 days of monitored pumping. The data has been ranked, with the highest yielding pump first, to show comparisons with the developed wells (highlighted) and undeveloped wells. During the operation of the dewatering system, pumps were routinely removed for servicing and maintenance. Power outages and maintenance to the air-compressor and pipe-work, resulted in periods when individual wells were not pumping. To allow a fair comparison of pumping data between wells, the data presented has been adjusted to represent continuous days of pumping, rather than days since installation. Four other wells were later commissioned in the Phase 1 well field, wells 720, 722, 725 and 729. These are not included below. More detailed well data can be found in Appendix D.

	0 – 100 days		**100 – 200 days**		**200 – 300 days**	
Rank	**Well No.**	**Ave. yield (m^3/day)**	**Well No.**	**Ave. yield (m^3/day)**	**Well No.**	**Ave. yield (m^3/day)**
1	**734**	**0.56**	**716**	**2.35**	**716**	**2.30**
2	719	0.48	719	0.94	730	0.89
3	724	0.47	724	0.62	**734**	**0.88**
4	735	0.43	**717**	**0.58**	719	0.86
5	726	0.41	**734**	**0.58**	737	0.81
6	**717**	**0.37**	721	0.46	739	0.68
7	730	0.37	735	0.46	721	0.67
8	**731**	**0.37**	726	0.44	724	0.54
9	723	0.34	737	0.42	738	0.54
10	737	0.34	**731**	**0.41**	735	0.51
11	**716**	**0.33**	738	0.41	**717**	**0.48**
12	721	0.33	718	0.40	726	0.47
13	718	0.32	723	0.34	733	0.47
14	738	0.32	733	0.34	732	0.41
15	727	0.29	727	0.33	**731**	**0.39**
16	733	0.27	730	0.33	740	0.38
17	739	0.17	739	0.26	727	0.37
18	732	0.16	740	0.22	723	0.29
19	728	0.11	732	0.20	718	0.27
20	736	0.10	736	0.13	736	0.21
21	740	0.09	728	0.12	728	0.17
Mean*		0.30		0.40		0.51

* Mean does not include well 716

Table 6.2. Ranked well performance data from the Phase 1 area of the Rainham landfill, Essex 100, 200 and 300 days after development

The average daily yield for the Phase 1 well field is low in comparison to other leachate wells (average 8.4 m^3/day, Table 2.1). During the monitoring period, the average yield increased somewhat, from 0.3 to 0.5 m^3/day. The Phase 1 area is uncapped, and the increase in yield may reflect a seasonal increase in infiltration. The first 100 days of monitoring were during drier, early summer months (May to July) when infiltration would be at its lowest. Toward the end of the monitoring period (~November to January), well yields increased in response to greater infiltration.

From 0-200 days, the developed wells had daily yields slightly greater than the average for the well field. Between 200 and 300 days, the yields from the developed wells decreased somewhat, though the average for the well field increased. The distribution of flow rates is similar to those described in Section 3.2, and not unusual for low permeability material (Stedinger, 1980). It is assumed that the distribution shown in Table 6.2 reflects heterogeneity, rather than a positive or negative response to the development works.

During the second and third period of monitoring (100 – 300 days), well 716 delivered a considerably higher volume of leachate than all the other wells. Historical site records, show that this well may have been installed (unintentionally) in a gravel-filled drainage ditch that was built on the edge of a waste haulage road, that was abandoned and buried during landfilling. The high yield from this well (in comparison with other Phase 1 wells), may in part be due to greater leachate flow from the drain. The data from 716 has been included, but it may not be comparable with other wells in the well field.

Observation wells installed in the Phase 1 area, were monitored during the test period (Figure 6.2). No significant change in leachate level was observed, which would imply that no dewatering was taking place and that infiltration ≈ extraction.

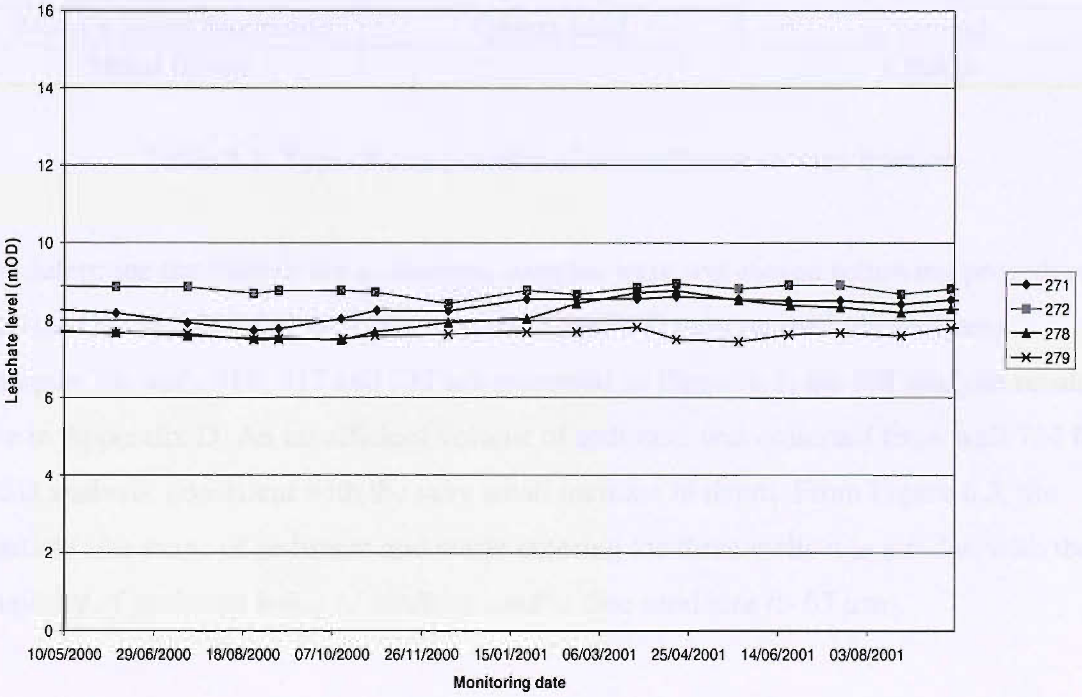

Figure 6.2. Leachate levels in observation wells during the monitoring period

6.2.4 Analysis of sediment recovered from wells

The material recovered from the wells can be classed as either:

- sediment entering the well from the waste formation through the well screen or,
- items or materials lost down the well whilst operating / maintaining pumps.

The items lost down the wells included 500 mm long eductor-pump filter nozzles and 100 mm length bolts. These larger items were not included in the PSD analysis. The composition of the sediment recovered from the wells was determined by visual inspection following sieving. The typical composition of the samples according to particle size is shown in Table 6.3. The majority of the material entering the wells consisted of quartz sand with charcoal, glass, brick and shell fragments, presumably sourced from the cover soils placed between lifts of waste, rather than the waste itself.

Fine to medium sand	**Medium to coarse sand**	**Gravel**
63 - 425 µm	**425 µm - 2 mm**	**2 - 20 mm**
Quartz sand	Wood + paper fibres	Plastic bag fragments
Charcoal	Glass flint brick shell	Rag /string
Glass brick	Charcoal	Flints
Wood + paper fragments	Quartz sand	Charcoal
Metal filings		Clinker

Table 6.3. Typical composition of the sediment by size fraction

To determine the PSD of the sediments, samples were wet-sieved following procedures outlined in BS 1377-2 (1990). The results of the PSD tests on the bulk sediment samples for wells 716, 717 and 731 are presented in Figure 6.3, the full analysis results are in Appendix D. An insufficient volume of sediment was collected from well 734 for PSD analysis, consistent with the very small increase in depth. From Figure 6.3, the particle size range of sediment and waste entering the three wells was similar, with the majority of sediment being of medium sand to fine sand size (> 63 µm).

Experiments by Terzaghi *et al.* (1996), have shown that aquifer particles smaller than 0.1 × $D_{15filter}$ can pass through a well graded granular filter. A 20 mm gravel with a D_{15} of around 10 mm was used in the Rainham wells. The gravel filter should permit a maximum particulate size of approximately 1 mm (and smaller) to pass into the well. In

Figure 6.3, between 90 and 95 % of the material analysed is < 1 mm. This shows, that although the gravel pack is acting well as a filter for all material greater than 1 mm, the high degree of sediment deposition in the wells (Table 6.1) demonstrates that the gravel is too coarse for the formation. From Table 6.3, the source of the fines is the intermediate cover soils, with some degraded waste and larger waste pieces.

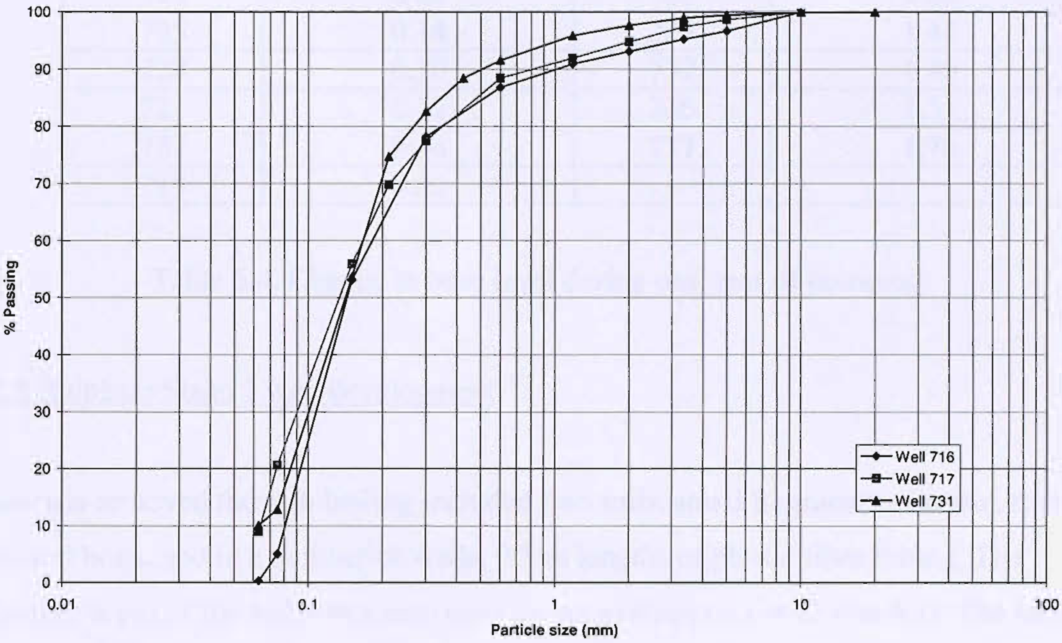

Figure 6.3. Bulk sediment samples from the collection tank following the development of wells 716, 717 and 731

6.2.5 Fresh sediment deposition

As part of the development works, deposited sediments were removed from the well liner to clean each well to its original drill depth. Well base level data from the Stage 1 development works are shown in Table 6.1. In three out of the four wells developed, a significant increase in the depth of the well was obtained. Table 6.4, shows the change in the base level inside the well liner over the monitoring period, which represents the volume of fresh material deposited in or removed from the well bore over time. The developed wells show either an increase or decrease (due to sediment removal in the pumps) in base level. There was no clear relationship between volume of sediment deposited and volume of leachate pumped.

Well	Change in base (m)	Well	Change in base (m)
731	**-0.73**	**734**	**0.54**
726	-0.40	718	0.77
730	-0.40	739	0.77
733	-0.14	740	0.81
724	-0.13	**716**	**0.85**
738	0.03	727	1.32
735	0.14	723	1.44
728	0.30	732	1.46
721	0.32	736	1.51
737	0.46	**717**	**1.76**
719	0.53		

Table 6.4. Change in base level during one year of pumping

6.2.6 Rainham Stage 2 well development

Materials removed through bailing included fine soils, small fragments of waste, metal nuts and bolts, and in a number of wells, 0.5 m lengths of plastic filter tubing. The effective depth of the wells was increased by an average of 2 m (Table 6.1). The larger diameter shell used in this stage of the well field development proved to be more effective in removing the larger fractions of waste.

The overpumping technique also successfully removed a considerable amount of sediment from the wells. However, the maximum particle size of the material that could be lifted was restricted to the diameter of the filter openings on the pump inlet. Because of this, the overpumping technique could only remove the finer fractions of material from the well, and not the larger pieces of waste and objects removed using the bailer. The over-pumping technique increased the effective depth by an average of 1.28 m.

Tables 6.5 and 6.6 present daily pumping average for 100 days before and 100 days after wells were developed. For those wells that were developed using surge and bail techniques, almost 70 % of wells showed a subsequent decrease in yield over 100 days of pumping, with a reduction in yield of between 1 and 89 %. For those wells that showed an improvement in yield, daily flow rates increased between 8 and 61 %. For those wells developed using over-pumping methods, all but one well showed a decrease in performance following development, with a range between 21-92 %. There was no improvement in yield from any well after being developed.

During the monitoring period, leachate levels were monitored in four observation wells to monitor dewatering and saturated depth (Figure 6.2). Monitored levels did not change significantly during the 200 day monitoring period, which would suggest that no dewatering has taken place.

Well No.	**Average daily yield before development (m^3/day)**	**Average daily yield after development (m^3/day)**	**% increase or decrease in daily yield following development**
717	0.37	0.04	89 % decrease
718	0.35	0.05	86 % decrease
719	0.75	0.69	8 % decrease
720	0.43	0.54	**26 % increase**
721	0.49	0.45	8 % decrease
722	0.16	0.15	6 % decrease
724	0.54	0.44	19 % decrease
725	0.35	0.44	**26 % increase**
726	0.58	0.35	40 % decrease
729	0.18	0.29	**61 % increase**
731	0.38	0.41	**8 % increase**
734	0.70	0.69	1 % decrease

Table 6.5. Average daily yield data for wells developed using surge and bail techniques

Well No.	**Average daily yield before development (m^3/day)**	**Average daily yield after development (m^3/day)**	**% increase or decrease in daily yield following development**
723	0.31	0.14	55 % decrease
727	0.34	0.34	no change
728	0.14	0.11	21 % decrease
732	0.30	0.18	40 % decrease
735	0.50	0.08	84 % decrease
737	0.61	0.44	28 % decrease
739	0.73	0.06	92 % decrease
740	0.27	0.03	89 % decrease

Table 6.6. Average daily yield data for well developed using over-pump techniques

6.2.7 Fresh sediment deposition

The base level within wells was monitored during pumping. Changing base levels represent that volume of fresh material that is either deposited in the well bore or, where base levels have fallen, material that is scoured from the well and is not replaced with fresh deposits. Table 6.7 and Figure 6.4 present base level data from the inside of the each well approximately 150 days after development. Well 730 was not pumped during the monitoring period. The data shows the volume of sediment deposited normalised against volume of leachate pumped form the well.

Well Number	**Development stage**	**Volume of sediment (m^3)**	**Volume pumped since development (m^3)**	**Vol. sediment / vol. leachate (m^3)**
716	1	0.021	351.24	8.3×10^{-5}
717	1 & 2	0.054	16.80	4.1×10^{-3}
731	1 & 2	-0.015	91.75	-2.6×10^{-4}
734	1 & 2	0.023	159.92	2.1×10^{-4}
718	2	0.049	9.38	5.8×10^{-3}
719	2	0.064	88.11	7.5×10^{-4}
720	2	-0.015	76.07	-2.1×10^{-4}
721	2	-0.005	97.38	-7.8×10^{-5}
722	2	-0.021	34.15	-9.6×10^{-4}
724	2	0.051	80.27	6.5×10^{-4}
725	2	-0.035	48.68	-7.4×10^{-4}
726	2	0.044	76.63	9.7×10^{-4}
729	2	0.018	14.15	1.3×10^{-3}
723	2	-0.014	31.53	-9.8×10^{-4}
727	2	0.004	66.37	1.3×10^{-4}
728	2	0.013	21.23	1.3×10^{-3}
732	2	0.004	36.55	1.9×10^{-4}
735	2	0.004	35.04	9.8×10^{-4}
737	2	0.006	74.46	8.9×10^{-5}
739	2	-0.004	18.54	-4.1×10^{-5}
740	2	0.005	8.36	9.7×10^{-5}
730	n/a	0.000	0.00	n/a

Table 6.7. Sediment volumes deposited / scoured from wells during 150 days of continuous pumping

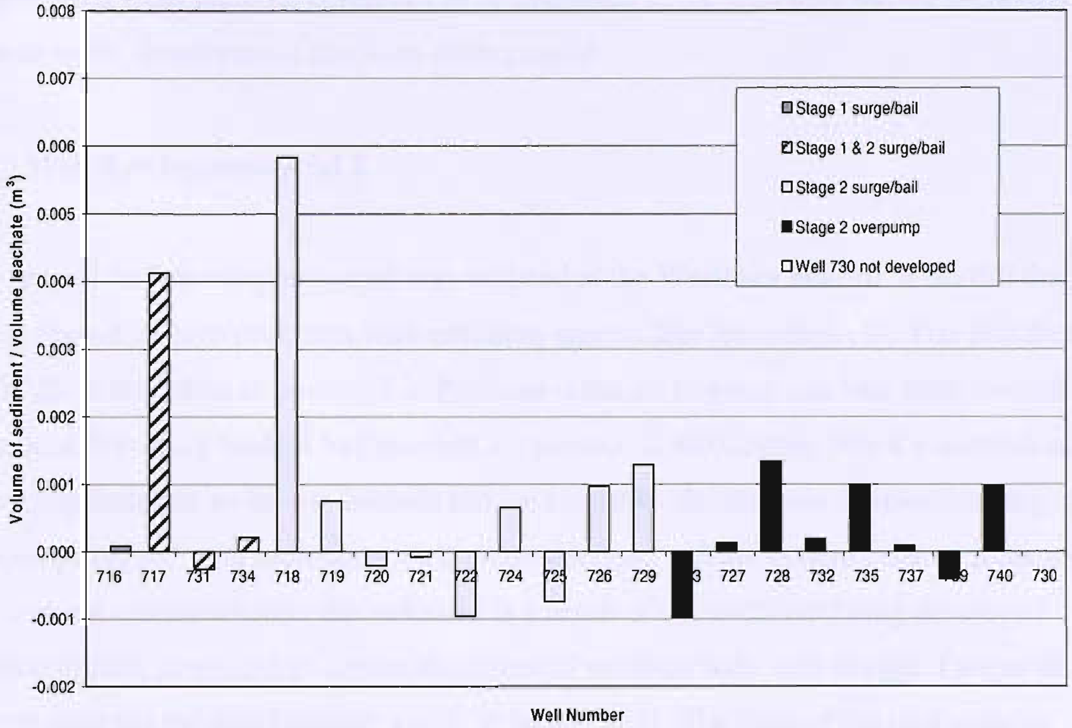

Figure 6.4. Sediment volumes deposited / scoured from wells during 150 days of continuous pumping

After the wells were developed, fresh sediments were deposited in 67 percent of the wells, increasing base levels by an average of 0.5 m. In these wells, the amount of sediment entering the well is greater than the volume of sediment being removed from the well through pumping (i.e. carried in suspension through the pump). In wells where base levels have decreased, sediments within the well bore have been removed by pumping (scouring) and fresh sediment ingress is limited or equal to removal. The average decrease in base level was 0.63 m. The amount of sediment deposition / scouring, was not a function of the volume of leachate pumped.

Where base levels have decreased, well development has cleaned and improved the efficiency of the pack by removing sediments from the near waste that would otherwise be washed into the well during normal operation. Scouring of existing sediments due to turbulence in the well bore has removed sediments and with no fresh material ingress, the base level has declined. The four wells that showed an increase in performance after they were developed (720, 725, 729 and 731) are wells that showed a decrease in base level during monitoring. In these wells, more sediment was scoured than was deposited. For these wells, development can be considered to have been successful: well yields have improved, and no fresh material has entered the well. In all other wells, yields have fallen, and fresh material continues to be deposited in the well bore during pumping. For these wells, development has been unsuccessful.

6.3 Well development trial 2

A second well development trial was initiated at the Westbury landfill, a landfill that was known to have problems with sediment ingress into leachate wells. The Westbury landfill is described in Section 7.2. Previous attempts to pump leachate from vertical wells at Westbury landfill had resulted in operational difficulties. When a network of recently installed wells was initially pumped in 1998, the leachate distribution ring main rapidly clogged with sediments, well yields declined and the system became inoperable. It was not certain whether the sediment is a result of the wells not being developed when drilled, or related to a more fundamental problem with well design. Two wells were selected for development; wells, W36 and W31. The aims of the trial were to:

- Collect representative samples of material from the wells for analysis, and to provide particle size data to aid future well screen design,
- Quantify any change in discharge rates and sediment ingress following well development.
- Monitor the performance and effectiveness of development in stopping new sediment entering the well.

From drilling and installation logs, the following installation details were known (Table 6.8).

Well No.	**Well Design**	**Original drill depth (mOD)**	**Well depth before development (mOD)**	**Leachate Depth before development (mOD)**
W31	150 mm steel screen (20 mm pack)	29.20	39.11	56.08
W36	150 mm steel screen (20 mm pack)	41.60	46.47	56.64

Table 6.8. Details of wells included in well development trial 2, Westbury landfill, Wiltshire

A bailer / surger operated from a cable-percussive drilling rig was selected as the most suitable technique to use for sediment collection, and because some of the other methods would require a large supply of water, which was not practical on this site (Section 3.5).

The development method was the same as that described in Section 6.2.1.

By removing sediment from the well, the original installation depth of the well was reached, increasing the effective depth 5.7 and 10 m. In well W36, after 24 hours when the well had recharged fully, no fresh sediments had entered the well. Some sediments did re-enter well W31, though these may have been suspended solids that had settled out of the leachate column when the well recharged (there was little drawdown in the well during the development).

6.3.1 Pumping tests

Prior to the well development works, the two wells were pump-tested to determine yields and efficiency (specific capacity). The wells were tested again after development to assess any change in performance. The results of each test are shown in Table 6.9.

		Base level (mOD)	**Leachate level (mOD)**	**Depth of pump (mOD)**	**Duration (hours)**	**Sw (m)**	**Well yield (m^3/day)**	**Specific capacity (m^2/day/m)**
W36	Before	46.49	55.14	52.58	24	1.50	32	21.33
	After	41.66	58.15	42.58	24	2.62	48	18.32
W31	Before	39.11	56.08	50.25	24	1.24	24	19.35
	After	29.21	56.07	34.25	24	1.21	7.2	5.95

Table 6.9. Pumping test data from wells W36 and W31 before and after well development

The data show that even before the development works, both wells yielded significant volumes of leachate despite the reduced effective depth due to sediment deposition. The specific capacity of the wells was similar between 19 and 21 m^2/day/m drawdown. Following development, the efficiency of both wells had decreased, between 14 and 69 %, wells W36 and W31 respectively.

Well W31 was installed in the SW area of the Westbury landfill and well W36 in the NW area (see Section 7.2). At this landfill, fine grained, unconsolidated industrial waste was co-disposed with MSW, with more industrial waste the SW area. The greater proportion of fines in the waste around well W31 may account for the greater decrease in performance (compared to well W36) after the well was developed. Further testing of these wells, alongside newly installed wells with fine-grained filter packs, will be discussed Section.7.3.

6.4 Analysis of well development data

Developing newly installed wells serves two purposes: to remove any residual drilling debris or residues from the filter pack or borehole wall which might otherwise impair well efficiency, and to remove any drilling or development debris from inside the well liner before installing the submersible pump (Preene, 2001). Developing a well will also remove material that has migrated into the well and has been deposited in the well bore over time, increasing the effective depth.

Individual well pumping data shows, that in all but four of the 23 wells developed (80 %), well yields decreased (between 1 and 89 %, average 44 %) following development. The four wells that showed an improvement in performance following the development works, were those developed using the surge and bail technique. No wells developed using the over-pumping methods demonstrated an increase in performance.

Monitoring data from unpumped observation wells, shows no or little dewatering was taking place over the monitoring period. The reduction in performance is therefore not due to a decrease in saturated depth in the waste. Field tests (Packman, 1990) and laboratory experiments (Wendling *et al*, 1997), have demonstrated that in unconsolidated material, soil particles (that would in normal pumping remain in the formation) will migrate to the well under the strong hydraulic gradients produced during development. It is proposed, that the development process discussed above may have caused the invasion of fine-grained, unconsolidated material into the pack and aquifer around the well due to the high velocity flows created during surging and overpumping. The mixing of the two materials produced a material of reduced permeability. This was especially true where the pack lay against intermediate cover soils. Exhumations of two developed wells (Section 4.3) showed evidence of the invasion of soils (from daily cover material) in the gravel pack. This physical clogging of the pack was not observed in an undeveloped well that was also exhumed. Sediment samples, from these wells (Table 6.3), suggest that the source of the fines is cover soils and some degraded waste. During the exhumation works, horizontal bands of daily cover soils were observed. In the developed wells, where the pack lay against a horizon of soil, it was fully contaminated with total occlusion of voids (Figure 4.7). Where the pack lay against waste, and in the well that was not developed, the pack was clean and free running. This is demonstrated in Figure 6.5. Where the soils have invaded the pack, the hydraulic conductivity is reduced. Further, alternating horizons of cover material with a lower hydraulic conductivity than the wastes will act as aquacludes, restricting the downward migration of leachate (Burrows, 1997). Where a well penetrates a layered section of waste, the well and filter pack form a zone of higher hydraulic conductivity through the less permeable soil horizons. If the pack becomes clogged during development, the preferential pathway is lost. Development of wells, where fine-grained unconsolidated material is present (for example, in the form of daily / intermediate cover), may therefore, not be suitable for landfill.

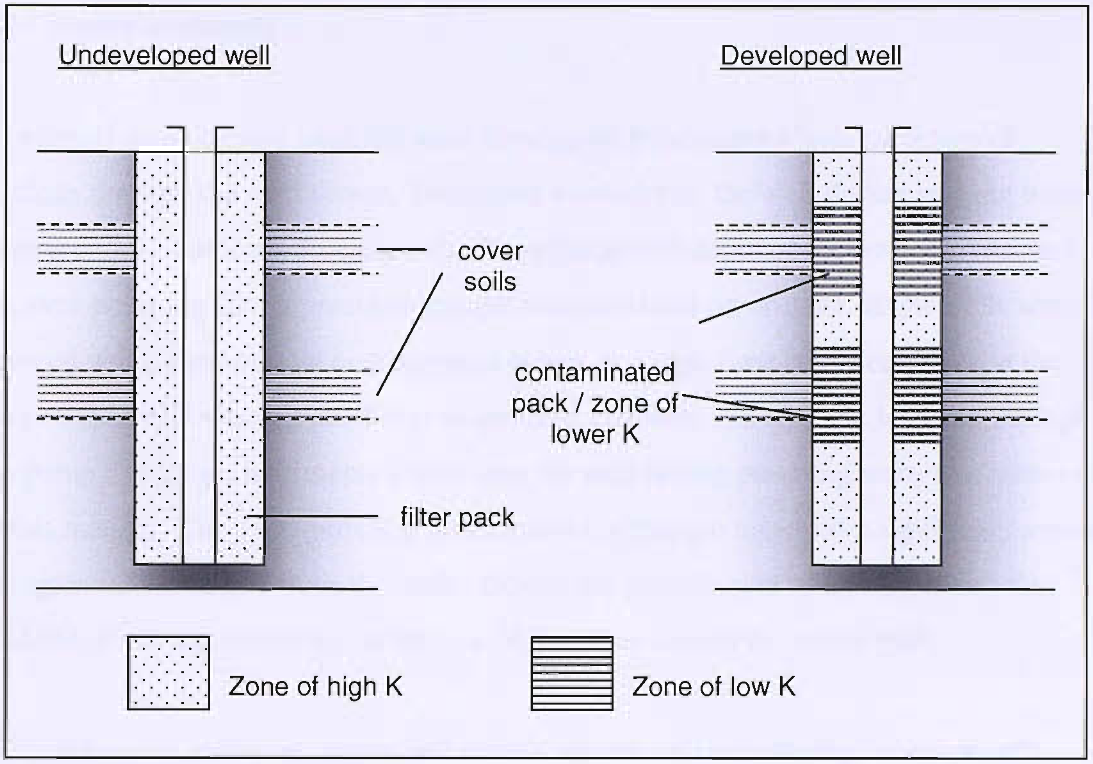

Figure 6.5. Contamination of pack from cover soils as a result of well development

The principle of the surging process is to induce a forward/reverse flow in the well, through the screen slots, gravel pack and formation, in order to break-up and disperse any clogging media. A bi-directional flow is applied because this will help prevent the bridging of fines in the pore spaces, a process that may occur with unidirectional flow (Howsam, 1990). In unconsolidated formations and gravel packs, effective well development must, therefore, induce grain agitation to prevent bridging and clogging. The overpumping technique used in stage 2, would have produced predominantly unidirectional flow to the well (reverse flow was created by backwashing the well with water or leachate, see Section 3.5. The degree of backwashing was, however, restricted because the volumes of water and leachate available to pump to the well were limited). This may explain why the over-pumping techniques were not successful at removing sediments from the pack.

For future well installations, it is recommended that development is avoided on installation, and should only be considered if the effective depth of a well has been reduced significantly due to the deposition of deposits in the well bore. Deposits should be removed using a bailer, but surging of the pack should be kept to a minimum.

6.5 Chapter summary

A series of wells on two landfills were developed, by causing a surging action of leachate through the well screen. Sediments washed into the well during surging were removed using the shell. In each well, the original drill depth of the well was reached. An over-pumping development technique was also used on one site. Eight wells were pumped using a pneumatic displacement pump, at a high flow rate. Sediments at the base of the wells were agitated into suspension and removed with the leachate through the pump discharge. Sediments drawn into the well during pumping were also removed in this manner. The over-pumping development technique removed a significant amount of ingressed sediments from the wells, though the particle size of the sediments that could be lifted was restricted to the size of the filter around the pump inlet.

PSD analysis of sediments recovered from a number of wells during development, demonstrate that the material collecting in the well during pumping (and during the development) is mostly cover soils, with some small pieces of waste.

Exhumations of two developed wells, showed contamination of the pack by soils used as intermediate cover material. This was washed into the filter pack due to the high flow velocities created during the development. The contamination of the pack resulted in a lowering of the permeability of these zones, restricting leachate movement into the wells and lowering performance in 80 % of the wells.

Therefore, well development is not recommended in landfill wells where fine-grained intermediate cover soils or wastes are present.

Chapter 7

Installing new wells in landfill

7.1 Introduction

The landfill database discussed in Chapter 2, field exhumations and well monitoring data (e.g. Table 6.1), suggest that one of the main operating difficulties of using vertical wells in landfill, is the migration of fines to the well during pumping. Material washed into a well can accumulate in the well bore over time, significantly reducing the effective depth, and restricting pumping from the well. The source of the material may be degraded waste, soils from daily covers, from the formation of a well skin or from the gravel pack.

Well development techniques are available to remediate clogged wells (Section 3.5), but field trials suggest that the surging action created during development may cause packs to become clogged that would otherwise be free of debris. Following development, fresh material will migrate to the well. To prevent the migration of fines at the outset, a suitably designed well filter pack can be used to prevent material from reaching the well bore. In groundwater well installations, fine-grained filter packs and screens with a narrow slot-size are often used to prevent fine particulate material from entering through the well screen. Based on laboratory analysis (e.g. Sherard *et al.,* 1984a and 1984b), the grading of filter packs is usually determined by analysing the PSD of the formation. The filter pack should be fine enough to prevent the persistent movement of fines from the aquifer, coarse enough to be significantly more permeable than the aquifer, and be sufficiently uniform to allow installation by depositing underwater with minimum risk of segregation (e.g. Driscoll, 1987, Preene *et al.*, 2000). In the landfills discussed in Chapter 2, filter pack sizes ranged between 5-40 mm, with 40 % of wells installed with a 20 mm gravel pack. Monitoring data suggests that these coarse gravel filters are not preventing the migration of fines, but simply acting as formation stabilisers. If landfill wells were designed on a site specific basis, with filters graded to match the PSD of the waste, then it may be possible to limit the amount of fines entering the well.

The PSD of the waste (as a whole) in a landfill, will often not be known and difficult to estimate due to heterogeneity. In a unit volume of waste, individual grain sizes and material type can vary significantly. Boland *et al.* (1998), describes the heterogeneity of waste samples arising from five boreholes drilled in a UK landfill which had received predominantly MSW. Of the 102 samples collected from the boreholes, no two samples were considered the same. An alternative to the above filter criteria is therefore proposed, based on the PSD of sediments that have been deposited in *existing* wells. This will produce filters that are significantly finer than those used in existing wells.

In this chapter, the installation of new leachate wells, based on a site specific design criteria, will be discussed. The wells were installed in landfill containing a high proportion of fines, and a known problem of well clogging. The packs were tested in the laboratory to determine the potential for microbial clogging. Some of the new wells were developed on installation. Comparisons were made between newly installed wells developed and not developed, and between existing wells that had been developed.

7.2 Background information

The Westbury landfill is sited in an unlined clay quarry that supplied material to an adjacent cement factory. Waste materials from the cement production, predominantly the residues from the cement kilns (e.g. cement kiln dust, CKD), were co-disposed with MSW, and later only MSW was deposited. The drilling trials discussed were carried out in the restored NW and SW areas of the landfill.

The Westbury landfill was chosen as a suitable trial site for the new well installations because the trial areas were restored with no existing dewatering in operation that could otherwise interfere with pumping tests. The site also had historical problems with poor well performance, specifically with regard to the ingress of sediments into wells. A series of wells were drilled between 1995-1998 for leachate and landfill gas extraction. However, due to the high suspended solid content, the leachate extraction system failed, allowing leachate heads within the waste to rise above the site licence limits. During pumping, large volumes of sediments were deposited in the wells. In addition to greatly reducing the effective depth of the wells, pumps were damaged and pipe-work became blocked with solids. Although the degree of sedimentation is perhaps extreme (owing to the fine-grained CKD waste present in the landfill), research has shown, that the deposition of sediments in landfill wells is common (Powrie and Beaven, 2003, Joseph, 1997). 80 % of the wells in the data-base showed some quantity of sediment deposition in the well bore.

Before the new wells were installed, a site investigation was carried out to establish whether the results gained would be transferable / comparable to other landfills that do not contain CKD.

7.2.1 Waste and leachate properties

The NW and SW areas of the landfill contain CKD codisposed with MSW. The ratio of CKD to MSW is not known, though drilling logs from existing leachate wells, suggest that although CKD is present in all areas, there is significantly more MSW than CKD.

Fresh CKD is a fine, dry material that readily absorbs water. The characteristics of CKD are affected by natural variations in the raw materials used for cement manufacture, the type of process employed and the type of fuel used (USEPA, 1999). CKD particle sizes generally vary by kiln process type and range from 0-5 μm to greater than 50 μm. Samples of Westbury CKD, recovered from the landfill have been analysed in the laboratory to determine physical and chemical properties. PSD analysis indicates that the majority of the particles (almost 50 %) are within the range 60 to 200 μm (Figure 7.2). Landfilling CKD will alter the physical nature of the material, by conditioning with water, compaction and changes in mineral composition (Baghdadi *et al.*, 1995). Conditioning turns CKD into a monolith exhibiting hydraulic conductivities similar to compacted clay soil (Baghdadi *et al.*, 1995, Duchesne and Reardon, 1998).

The hydraulic conductivity of the waste in a number of areas of the landfill have been derived from pumping tests (Viridor, 1996, AERC, 2001). The values are broadly similar between 1.5×10^{-6} to 5.0×10^{-7} m/sec. This accords with values reported in the literature for the permeability of waste at a depth of ~30 m (e.g. Beaven, 1996), and those derived from landfill pumping tests in actual landfill wells (Giardi, 1997, Burrows, 1998). The specific yield (drainable porosity) of the waste in the NW area has been calculated at 12 % (AERC, 2001). From multiple well tests, at a number of sites, Burrows (1998) calculated specific yield values of between 9 and 16 %.

The pH and conductivity values for Westbury leachates are all slightly higher than the typical range of MSW leachate, most likely due to the presence of CKD mixed with MSW. COD, total organic carbon (TOC) and VFA levels in Westbury leachates from the SW area are within the typical range for an acetogenic landfill (Section 3.3.1), though some sulphate reduction may be occurring in the NW. A full analysis suite of leachate sampled from the NE, NW and SW areas of the Westbury landfill is reproduced in Appendix E.

A comparison between the Westbury landfill and a 'typical' landfill (see Section 2.2) is given in Table 7.1. Although the Westbury landfill differs in that it contain a high proportion of fines than would be expected to be found in a typical MSW landfill, in terms of waste age, leachate chemistry and hydraulic properties, the sites are comparable.

	Typical landfill data	**Westbury trial areas**
Waste type	MSW	MSW + CKD
Waste depth	23 m	21-29 m
Saturated depth	4-22 m	11-24 m
Waste age	< 20 years	~10 years
K	1×10^{-4} and 4×10^{-9} m/sec	1.5×10^{-6} to 5.0×10^{-7} m/sec
Specific Yield	9-16 %	12 %

Table 7.1. Specification of new well installations in comparison to typical leachate wells

7.3 New well designs

By using a suitably designed well installation incorporating a fine-grained filter pack and narrow screen slot-size, it is possible to prevent fine particulate material from entering well screens. Sediments, waste pieces and suspended particles will be filtered by the well pack and prevented from entering the well bore. However, as has been discussed in Section 3.3, one of the problems of using a conventional sand filter pack in the landfill environment is the potential for microbial clogging due to the high organic load and elevated temperature of the leachate. Laboratory and field tests suggest that the rate of microbial clogging will depend on a number of factors, but most significantly the grain size of the filter media used and the biological loading (e.g. Paksy *et al.*, 1998, Rowe *et al.*, 2000). If the proposed filter-selection criteria (basing the filter grade on existing well sediments) are used, then fine-grained sand packs may be effective at removing fines from the leachate, but with a consequent risk of clogging.

To test the feasibility of using a sand filter pack in a landfill well, laboratory tests were carried out to assess the microbial clogging potential of fine-grained filter sand (Wang and Banks, 2006).

7.3.1 Laboratory testing of filter packs

The apparatus consisted of ten filter column units set up to simulate the filtration process, these included 3 different filter pack grades and a single control with no filter media. Three grades of filter sand were used in the column tests: 0.235-0.45, 0.35-1.00 and 1.70-4.74 mm.

Each unit was filled with a 100 mm deep layer of graded filtration sand. An in-line filter was fitted to remove scoured biosolids from the recirculated leachate flow and a gas collection system was attached to collect and measure any gas generation (Figure 7.1). The temperature was kept constant at 35 °C.

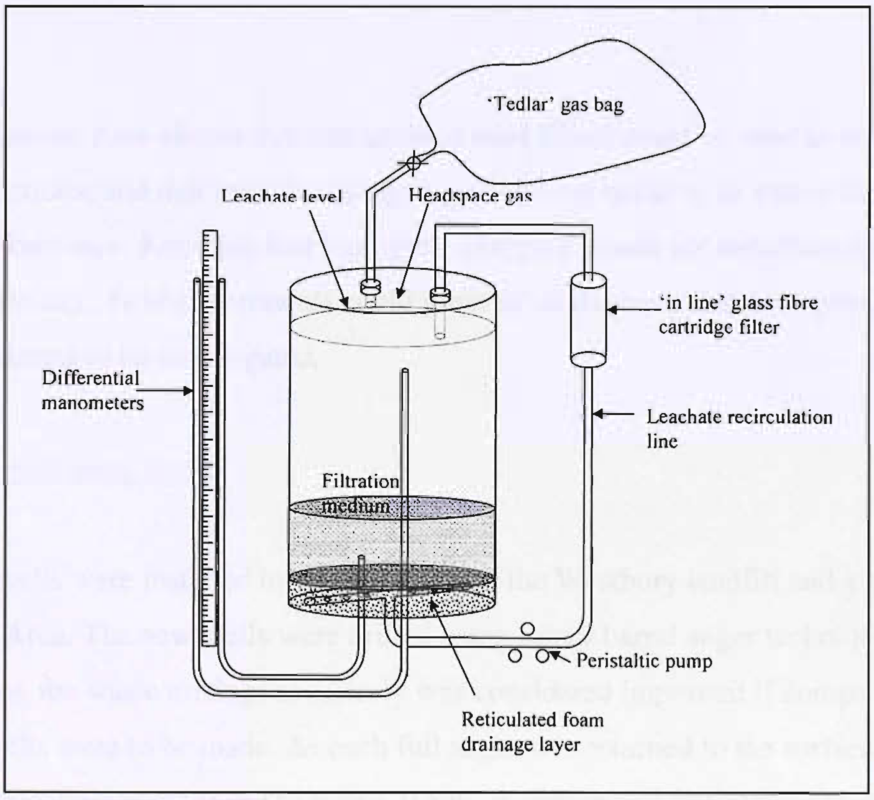

Figure 7.1. Laboratory filter clogging cell set-up (from Wang and Banks, 2006)

2 litres of leachate from the SW Area of the Westbury landfill was recirculated through each filter column at a controlled flow rate of 50 ml/min. The leachate had been filtered prior to installation to remove suspended solids. Although not representative of field conditions, it was considered important that only biological clogging was investigated and not the physical clogging of the filter sand due to the filtration of suspended particles. 5 ml samples of leachate were removed twice per week for analysis and replaced with fresh leachate. The leachate samples were analysed for pH, COD, VFAs and sulphate concentrations. The filters were operated for 220 days over four cycles. The reacted leachate was drained from the columns and replaced by 2 litres of fresh leachate at the start of each cycle. The microbial clogging potential was observed by taking differential manometer readings from manometers located in the drainage and reservoir sections of the reactor.

After four phases of recirculation, no significant biological clogging was apparent in any of the filter sands and head space gas analysis indicated that no methane gas had been produced in any of the columns. This suggests that sulphate reduction was the predominant microbial reaction and the methanogenic process was inhibited by the sulphate-rich alkaline leachate. No suspended biomass was collected from any of the columns.

The experiments have shown that fine grained sand filters could be used in new leachate well installations, and that microbial clogging would not occur to an extent that would impair performance. Knowing that biological clogging would not significantly affect well performance, field experiments could proceed on the basis that only physical clogging needed to be investigated.

7.3.2 New well installations

Two new wells were installed in the NW Area of the Westbury landfill and a single well in the SW Area. The new wells were drilled using rotary barrel auger techniques as the ability to log the waste arisings accurately was considered important if comparisons between wells were to be made. As each full auger was returned to the surface, the profile of the waste was logged to within 0.5 m. Borehole and completion logs for the new wells are given in Appendix E.

To work as an effective filter, the grain size of the filter sand had to be small enough to permit only the finest fractions of sediments to move into the well during pumping, but not so fine as to restrict the flow from the aquifer. The filter pack grading for the new wells was based on the PSD of sediments collected from existing wells in the NW and SW areas (Figure 7.2). These sediments represent particulate matter that had passed through the filter pack, and therefore represent the maximum particle size that could be transmitted through the filter pack, rather than the maximum particle size of the waste.

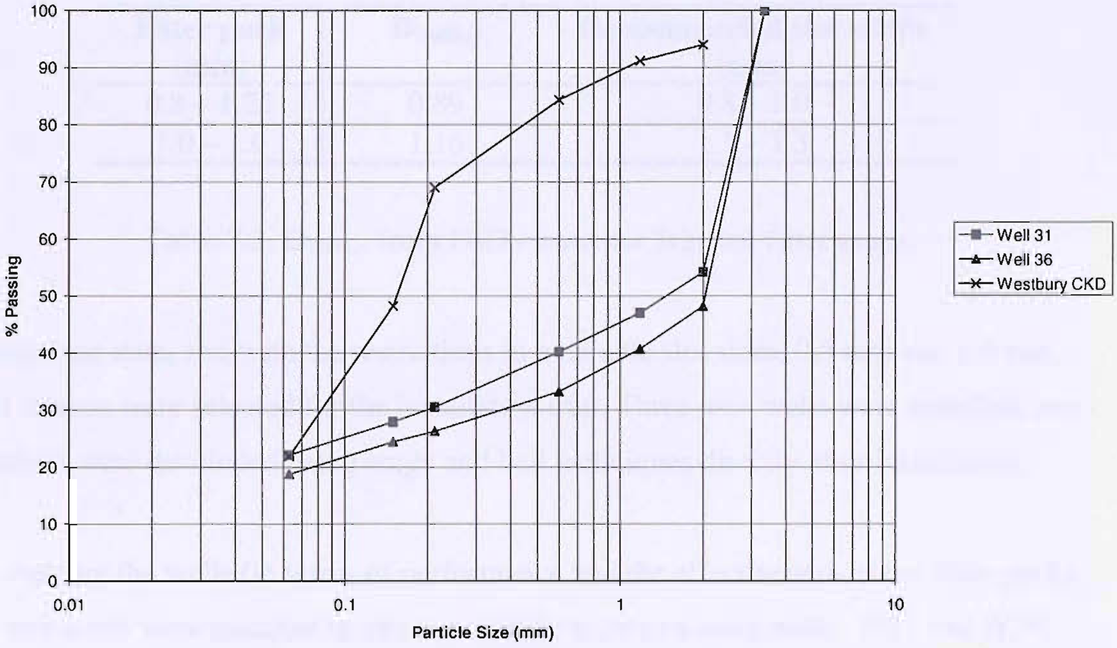

Figure 7.2. PSD for well sediment samples

Two filter packs were chosen for the installation trials 0.8 – 1.25 mm and 1.0 – 1.6 mm sand. Sherard *et al.* (1988a), have demonstrated experimentally, that aquifer particles smaller than 0.1 × $D_{15filter}$ can pass through a filter. For the chosen filter packs, the fraction passing equates to approximately 0.1 mm (Table 7.2). Based on the PSD of sediments that have entered existing wells (Figure 7.2), using the finer filter packs could result in a reduction in fines of between 75 and 80 %.

Filter pack	**$D_{15filter}$**	**0.1 × $D_{15filter}$**
0.8 – 1.25 mm	0.92	0.09
1.0 – 1.6 mm	1.2	0.12

Table 7.2. Sediment passing filter pack based on Sherard *et al.* (1988b)

The well screen opening size was selected to retain the filter material using the following rule (Driscoll, 1987):

well slot size = $D_{10filter}$

This gave slots that effectively retain 90 percent of the filter pack. Driscoll (1987) suggests that the slots can be +/- 8 percent of this. The $D_{10filter}$ of the filter packs selected and the recommended slot widths are given in Table 7.3.

Filter pack (mm)	**$D_{10filter}$**	**Recommended slot width (mm)**
0.8 – 1.25	0.89	0.8 – 1.0
1.0 – 1.6	1.16	1.1 – 1.3

Table 7.3. $D_{10filter}$ from PSD curves for selected filter sands

Using these data, and with the restrictions in available slot sizes, 0.5 mm and 1.0 mm well screens were selected for the installation trial. Three new wells were installed, two of which were developed using surge and bail techniques directly after installation.

To compare the wells (in terms of performance and the effectiveness of the filter pack), the new wells were installed in close proximity to two existing wells: W31 and W36. Drilling logs from these two wells indicated that the base of the site was between 24-35 m and the waste type was layered horizons of MSW and CKD. The two wells had been developed (Section 6.3).

Completion details of the wells, and of the existing wells, are given in Table 7.4.

Area	Well No.	Installation depth (mBGL)	Screen Type	Pack type
NW	36A	21	Stainless steel / 0.5 mm wire-wrapped 17 % open area	0.8 -1.25 mm sand
	36B (developed)	21	Stainless steel / 1.0 mm wire-wrapped 29 % open area	1.0 – 1.6 mm sand
	W36 (developed)	24	Steel / 5 x 100 mm cut-slots 25 % open area	20 mm gravel
SW	31A (developed)	35	Stainless steel / 0.5 mm wire-wrapped 17 % open area	0.8 -1.25 mm sand
	W31 (developed)	33	Steel / 5 x 100 mm cut-slots 25 % open area	20 mm gravel

Table 7.4. Installation details of wells tested

In each area, three boreholes were installed with dual-level monitoring piezometers. The lower piezometers were placed at the base of the landfill, the upper piezometers in the upper waste, 1-2 m below the level that leachate was struck during drilling. The two piezometers had 1.5 to 2 m response zones and are separated by a bentonite pellet and powder grout. Example installation details of a piezometer well can be found in Appendix E. A plan of the new and existing well installations is given in Figures 7.3 and 7.4.

Following the installation of the new wells, hydrogeological pumping tests were carried out to determine efficiency, clogging potential and to monitor the ingress of sediments through the filter pack of each well.

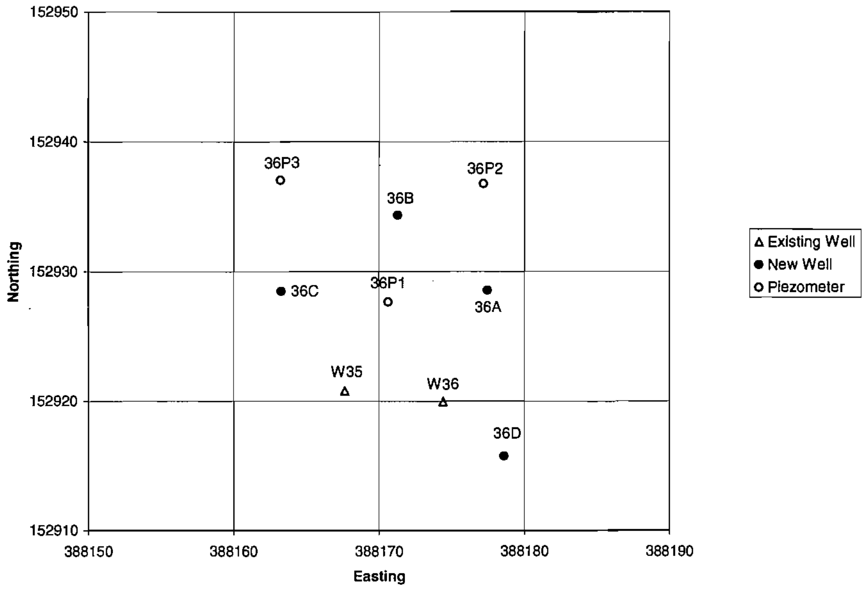

Figure 7.3. Well and piezometer locations, NW Area

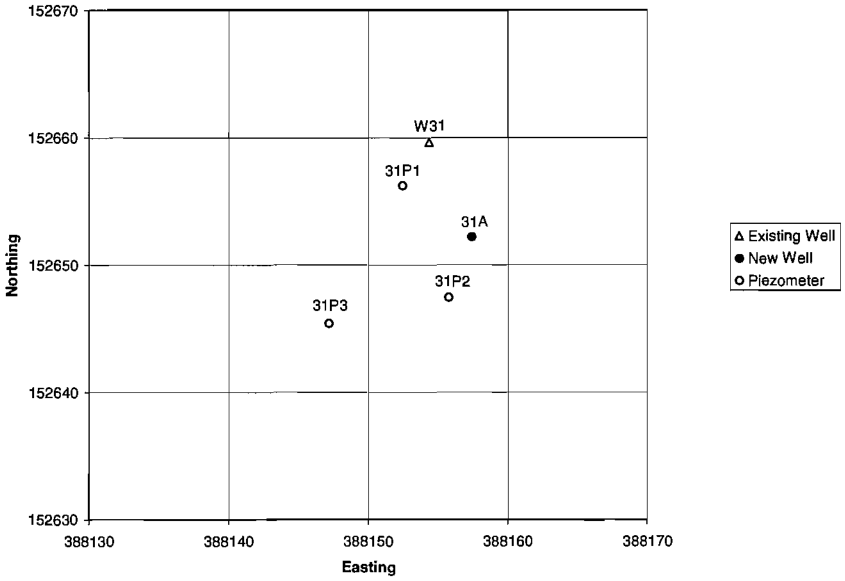

Figure 7.4. Well and piezometer locations, SW Area

7.4 Hydrogeological testing of new well installations

The new extraction wells and existing wells were pump tested to:

- characterise each well in terms of efficiency (well losses vs aquifer losses),
- compare the new installations with existing wells,
- compare a developed old well with a well-designed new well,
- monitor sediment ingress into the wells during pumping,
- collect leachate samples during long-term pumping,
- monitor performance over time.

The well designs tested are shown in Table 7.4.

A three-phase, 16 amp power supply was installed in each test area. A selection of electric submersible pumps was made available for the pumping tests. These included both 80 and 100 mm pumps of different capacities. The down-borehole pump discharged into a collection tank. A float operated sump-pump within the collection tank then discharged the leachate into a buried recirculation pipeline, at approximately 15 m depth, within the SE Area.

An automated flow controller was fitted between the submersible pump and the discharge tank. This monitored both flow and total volume, and maintained steady flow from the pump to within +/- 5 %. With the pumps available for the pumping tests, the lowest discharge rate that could be maintained constant using the flow controller was 0.5 m^3/hr. The flow meter was tested periodically for accuracy using a bucket and a stop-watch to measure directly the volume discharged over time.

7.4.1 Constant discharge tests

Long term constant discharge tests were carried out in each well. Wells W31 and W36 were pump tested before and after they were developed. The effects of dewatering during pumping were assessed by monitoring leachate heads in the pumping well and observation wells in the test area. The test procedure was adapted from BS 6316, 1992.

The duration of each test ranged from 1 to 14 days pumping, followed by approximately 7 days recharge. The specific capacity of the wells at steady state is given in Table 7.5.

Well No.	**Q (m^3/hr)**	**Sw (m)**	**Specific capacity m^2/hr/m**
36A	2.4	5.40	0.44
36B (developed)	1.5	2.31	0.65
W36 (pre-development)	1.3	1.5	0.89
W36 (post-development)	2.0	3.61	0.55
31A (developed)	0.5	1.22	0.41
W31 (pre-development)	1.0	1.24	0.81
W31 (post-development)	0.3	1.21	0.25

Table 7.5. Discharge and drawdown data for constant discharge tests

Pre-development, wells W31 and W36 were the most efficient wells. Of the three new installations, 36B was the most efficient. Following development, the specific capacity of the well W31 and W36 fell. Reasons for the reduction in yield following development were discussed in Section 6.4. These included the invasion of the pack by cover soils and the restriction of flow paths to the well.

7.4.2 Step drawdown tests

Based on the response of the constant discharge test, short term step-drawdown tests were conducted in the NW area wells to evaluate performance in terms of well loss (head losses within the bore-hole, filter pack and well screen) and formation loss. The wells 31A and W31 were not tested due to faulty pumping equipment.

The test procedures and results analysis for step-drawdown tests are described in Section 5.3.1. Changes to these procedures included:

- running only three steps,
- the extension of the duration of the third step.

The pump was placed approximately 1 m above the dipped base of the well. The duration of the first two steps was 200 minutes, the final step ran overnight for approximately 1000 minutes. Time / drawdown (Sw) for each test is shown Figure 7.5.

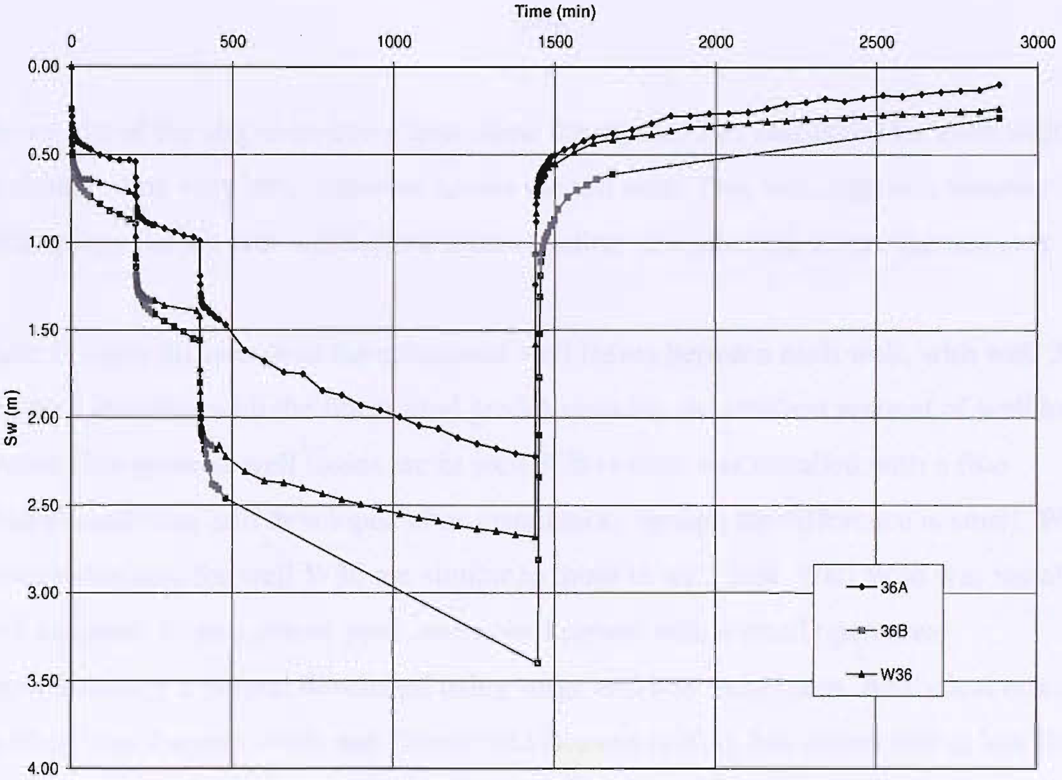

Figure 7.5. Step-drawdown test results in wells 36A, 36B and W36

Using the Hantush and Bierschenk (1963, in Krussman and de Ridder, 1994) method of step-test analysis, the values of B and C have been calculated for each pumping test. Where Q = 1, the calculated values and estimated drawdown (Sw) are presented in Table 7.6. More detailed analysis is given in Appendix E.

Well No. & pack size	**B**	**C**	**BQ (m) Aquifer loss**	**CQ^2 (m) Well loss**	**Sw (m) ($BQ + CQ^2$)**
36A (0.8-1.25 mm)	0.506	0.064	0.51	0.06	0.57
36B (1.0-1.6 mm) Developed	0.356	0.245	0.36	0.25	0.61
W36 (20 mm) Developed	0.531	0.220	0.53	0.22	0.75

Table 7.6. Hantush and Bierschenk (1963) analysis of Westbury wells step drawdown data

The results of the step drawdown tests show the aquifer loss calculated for each well to be similar, with very little variation across the test area. This was expected, because the drilling logs for the new wells show little variation in waste type across the test area.

There is some difference in the calculated well losses between each well, with well 36A (the well installed with the finest sand grade) showing the smallest amount of well loss overall. The greatest well losses are in well 36B (which was installed with a fine-grained sand filter and developed after installation) though the difference is small. Well losses calculated for well W36 are similar to those in well 36B. Well W36 was installed with a coarse, 20 mm gravel pack, and a well screen with a small open area (approximately 3 %) and developed using surge and bail techniques. Analytical research by Clark and Turner (1983) and Powrie and Beaven (2003), has shown that at low flow rates, head loss across well screens, even with such a small percentage open area, is minimal. The head loss through the gravel would also be expected to be small, unless the gravel had become clogged (Barker and Herbert, 1992a). The well losses calculated from the step drawdown tests, therefore, indicate clogging in the pack caused by the migration of fines during development (see Section 6.4).

In terms of well performance and drawdown in the borehole, at low flow rates (~ 8 m^3/day, the average for landfill wells (Table 2.1)), there is little difference between the well installations, however, development does show an impact on the well loss component of the system.

7.5 Filter pack effectiveness and sediment deposition

The effectiveness of each well design was determined by monitoring the volume of fresh material entering through the well screen during pumping. To calculate the volume and physical characteristics of the material entering the wells:

- samples of leachate were collected from the discharge pipe to analyse for total suspended solids (TSS),
- the base level in each well was regularly measured to monitor the volume of sediment being deposited, and
- samples of sediment from the base of the pumping wells were recovered using a hand bailer for PSD analysis.

7.5.1 Total suspended solids and deposition

Suspended solids are organic and inorganic particles that either float on the surface of, or are held in suspension in, the leachate. Particles washed through the filter pack and well screen may be held in suspension by agitation or flow toward the pump, and may settle out of the leachate if flow stops (for example, if the pump is switched off). To determine the quantity of suspended solids in the leachate during pumping cycles, 250 ml samples of leachate were taken at regular intervals from the discharge pipe during the pumping of the three new wells and the existing well. The analysis method was as follows:

- A 25 ml sample of agitated leachate was vacuum-filtered through a weighed glass-fibre filter paper. The filter paper (Fisherbrand MF200) had a minimum particle retention of 1.2 μm.
- The residue retained on the filter was washed, under vacuum, with de-ionised water to prevent dissolved solids within any retained leachate affecting the results.
- The residue and filter were oven dried at 103 to 105° C for 24 hours.

- The filter paper and residue were reweighed.
- The gain in weight was a dry-weight measure of the particulates present in the leachate sample.

The results of the total suspended solids analysis are given in Appendix E and Figure 7.6.

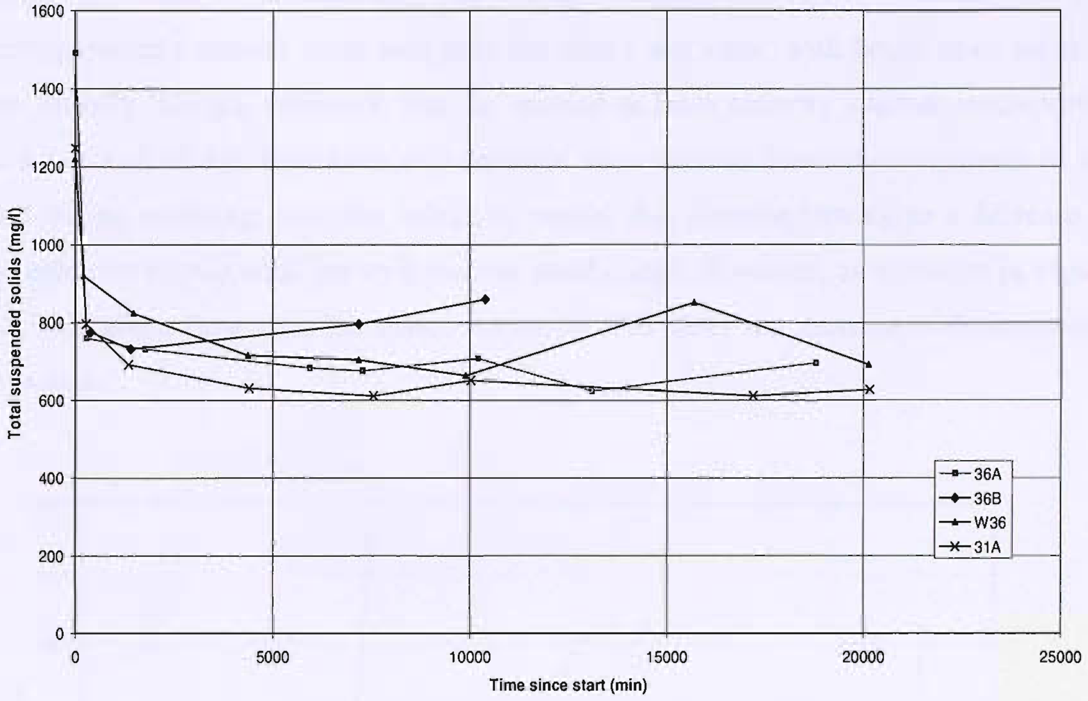

Figure 7.6. Total suspended solids count (mg/l) in leachate samples taken during the pumping of wells 36A, 36B, W36 and 31A

In all wells, the suspended solids concentration is high (between 1492 - 1220 mg/l) at the start of pumping. After approximately one hour, the concentration has decreased by between 33 and 50 percent. No leachate sample was collected at the start of pumping from well 36B, but after 6.5 hours, the TSS concentration is similar to the other wells.

The leachate analysis has shown that at the start of pumping when the pump is first activated, there will be an initial flush of sediments mobilised through the filter pack and well screen and carried in suspension through the pump. As pumping continues, the concentration of suspended particles falls rapidly, until concentrations remain relatively constant for the duration of the test. The grading of the filter pack did not influence the concentration of suspended material entering the well.

The concentration of suspended solids being transported in a given volume of fluid will be determined partly by the velocity of the fluid at the time of measurement (Stelczer, 1981). The flow velocity will also control the limit particle size (the maximum fraction becoming suspended by the particular flow velocity and all finer fractions being transported in suspension). Bonaga (2000), demonstrated, that at low waste densities, the mass of particles washed into a well could be related to entrance velocities. For a given flow rate, more material was washed through the smaller slot-size with a correspondingly smaller open area than the larger slot sizes, with larger open areas. It was initially thought, therefore, that the amount of fines entering leachate wells would be a function of the drawdown and entrance velocities: as drawdown increases in the well during pumping, entrance velocities would also increase (owing to a decrease in the effective depth) until the well reaches steady state. However, as is shown in Figure 7.7, at a given flow rate, the concentration of TSS does not increase with increasing drawdown.

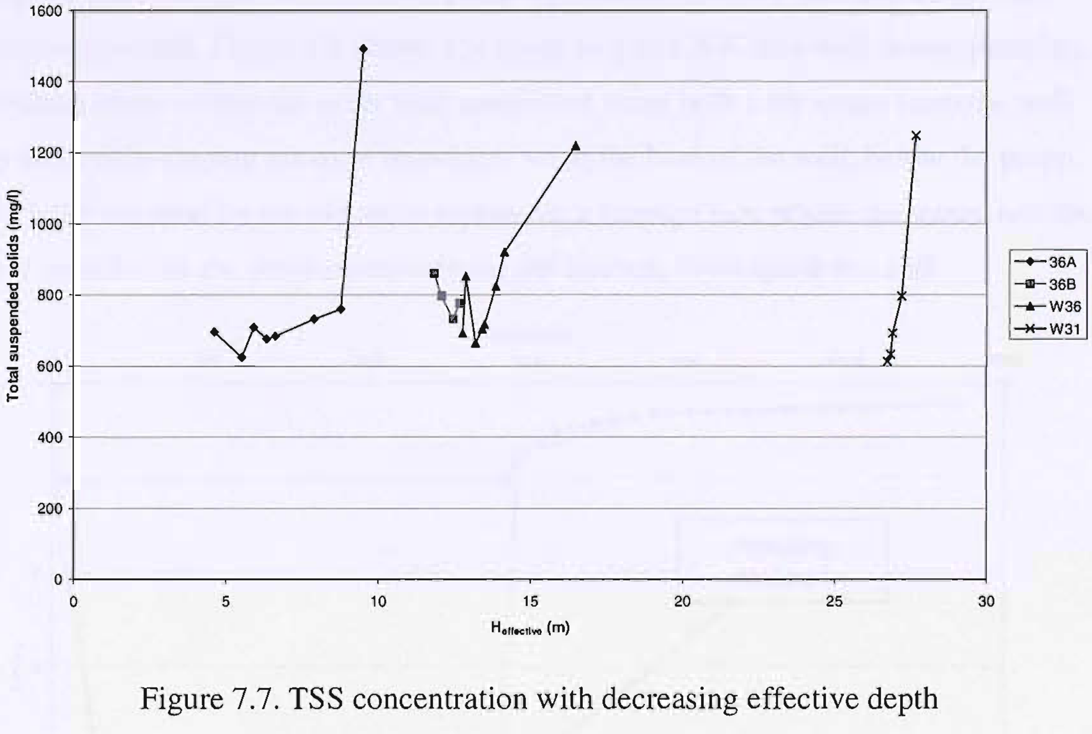

Figure 7.7. TSS concentration with decreasing effective depth

The changing TSS concentration may be explained by the development of a seepage face in the well during pumping. When pumping occurs from a well in an unconfined aquifer, a seepage face develops between the elevation where the water table intercepts the well face and the water level in the well (Rushton, 2006) (Figure 7.8).

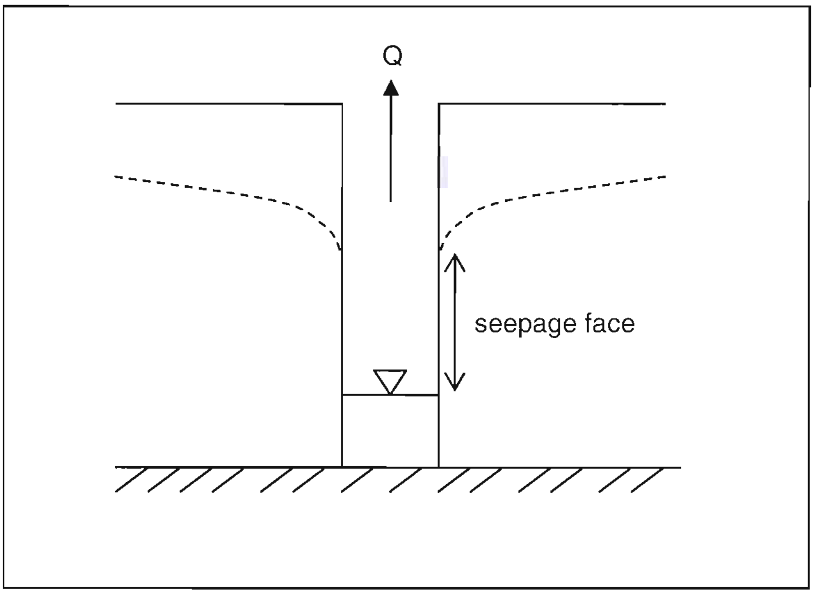

Figure 7.8. Seepage face in unconfined aquifers during pumping

Seepage faces were observed during pumping tests, in both new and old wells at the Westbury landfill. Figure 7.9 shows a seepage face in a NW area well during pumping. Leachate levels within the wells were monitored using both a dip meter from the well top and a data-logging pressure transducer set at the base of the well, below the pump. The level recorded by the dip meter represents a seepage face within the waste, and the level recorded by the pressure-transducer, the leachate level inside the well.

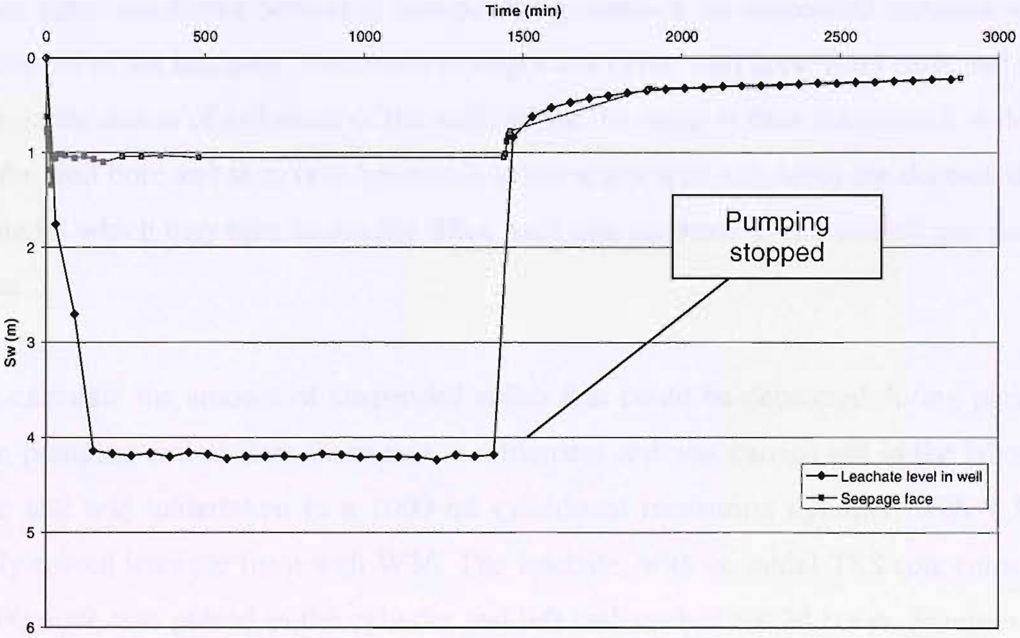

Figure 7.9. Leachate level in the well and seepage face in well 36C, NW Area, Westbury landfill

Analysis carried out by Al-Thani *et al.* (2004), on seepage faces in leachate dewatering wells, has demonstrated that the effect of drawdown in the zone of influence around a pumped well is less than commonly assumed, because the flow into the well occurs over a large depth of well screen even when the well is fully dewatered. When a well is initially pumped, and before seepage faces have developed, hydraulic gradients are predominantly horizontal. Consequently, the vertical distribution of flow rates into the well is related to the vertical variation in hydraulic conductivity with depth. Where the hydraulic conductivity of the waste reduces with depth, flow rates into the well are greatest in the upper saturated layers and reduce with depth. With continuous pumping over time, and as a seepage face develops, the hydraulic gradients in the immediate vicinity of the well change from being predominantly horizontal to predominantly vertical. This may explain the initial flush of sediments into wells when pumping is first initiated. Flow from the aquifer will be high during the initial stages of pumping, consequently more particulate matter can be held in suspension and carried to the well. As pumping continues, hydraulic gradients become predominantly vertical, flow will be more evenly distributed and entrance velocities will be lower into the well, and the TSS concentration will rapidly fall as a result.

7.5.2 Suspended solids settlement test

Over time, and during periods of non-pumping, some of the suspended particles will settle out of the leachate. These will be deposited in the well bore, filter pack and waste within the radius of influence of the well. When the pump is then reactivated, turbulence in the well bore and high flow velocities in the upper well will scour the deposited material which may then be readily lifted back into suspension and carried into the well bore.

To calculate the amount of suspended solids that could be deposited during periods of non-pumping and as flow decreases, a settlement test was carried out in the laboratory. The test was undertaken in a 1000 ml cylindrical measuring cylinder, with 1 litre of fully-mixed leachate from well W36. The leachate, with an initial TSS concentration of 1700 mg/l, was placed in the cylinder and left undisturbed for 24 hours. Samples of the supernatant were taken at the beginning of the test and after 3, 6 and 24 hours. The suspended solids concentration was measured in each sample. The results of the settlement test are given in Table 7.7.

Settling time (hours)	**Leachate suspended solids (mg/l)**	**SS removal (%)**
0	1700	0
3	865	49.6
6	795	53.2
24	628	63.1

Table 7.7. Leachate settlement test result

The test indicates, that after 3 hours settlement almost 50 percent of the suspended solids present in the leachate were removed. Additional settlement time, however, did not achieve significantly higher SS removal, with a total of 63 percent reduction in concentration after 24 hours.

Intermittent pumping, with rapid draw-down followed by periods of recharge, will lead to the mobilisation and deposition of particulate matter in the well over time. The higher the rate of pumping, the greater the radial distance from the well over which fines may be mobilised.

7.5.3 Fresh sediment deposition

During pumping, there was a gradual deposition of fresh sediments in the newly installed wells at Westbury. By monitoring the base level of the well during pumping, an estimation has been made of the volume of fines entering and settling in the well bore. The cumulative volume of sediment (less the volume removed for analysis), for each well is shown in Table 7.8. The volume of sediment deposited, per given volume of leachate pumped is also shown. The volume of sediments deposited was greatest in well 36A, and least in 31A. When normalised against total volume of leachate pumped, however, the volume of sediment entering the wells per volume pumped is similar, with slightly more sediment entering well W36. Therefore, the grading of the filter pack, or developing the well on installation does not appear to have influenced the rate of sedimentation.

Well number	Approximate volume of sediment (m^3)	Approximate volume pumped (m^3)	Volume sediment (m^3) / volume of leachate (m^3)
36A	0.063	1400	4.3×10^{-5}
36B	0.014	400	3.5×10^{-5}
W36	0.018	800	5.1×10^{-5}
31A	0.005	150	3.1×10^{-5}

Table 7.8. Approximate volume of sediment entering wells per given volume of leachate pumped

7.5.4 PSD Analysis

During the course of the pumping tests, sediment samples were recovered from the base of wells 31A, 36A and W36 for PSD analysis. These were compared to sediment samples collected during well development (W36 and W31) and before pumping commenced (36A). The aim of the analysis was to observe if the sediment entering the different wells was similar (in terms of particle size) and also to see if the physical properties of the sediment changed over time, which could indicate clogging in the filter pack. The fraction of sediment < 63 μm in size was independently analysed using laser diffraction techniques. The analysis was carried out using a Coulter LS130 sedigraph, equipped with a Micro Volume Module, allowing the analysis of sediments between 0.43 and 63 μm in size. The PSD analysis results are shown in Figure 7.10.

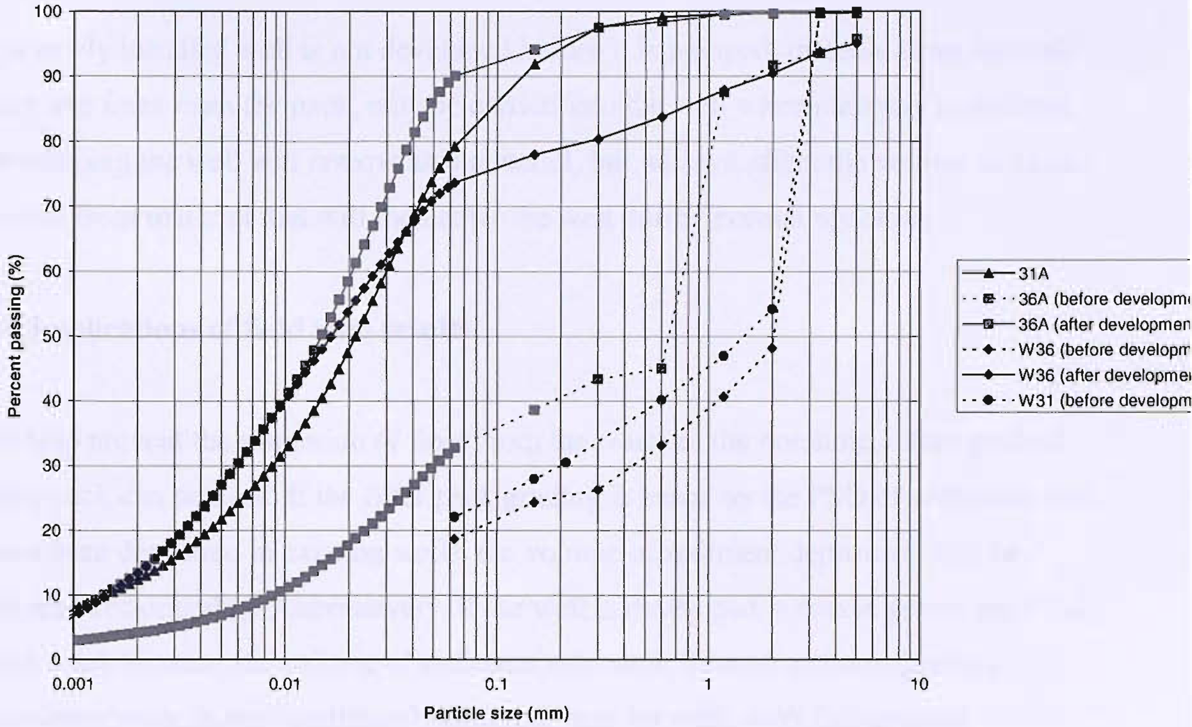

Figure 7.10 PSD of sediments collected from wells

Figure 7.10 compares the particle size of material being deposited in wells before and after development, and in well 36A, which was not developed, sediments deposited when the well was first pumped, and after several weeks of pumping.

Before the wells were developed, the PSD of the sediments range between fine sand and fine gravel, with between 55 and 60 % of the sediment > 1 mm, which is greater than the theoretical maximum for the gravel pack used (see Section 3.4.3). In the well that was not developed, the majority of the sediment is again larger in size than would be expected for the filter pack used (0.8-1.25 mm), with up to 65 % of the material > 0.1 mm (the theoretical maximum for the filter). This would suggest, that the material collected from the wells is not just sediment that has passed through the filter during pumping, but material that was present in the well at the time of installation or is from the pack itself.

Following development, the grain size of fresh material deposited in the well was significantly finer, with only 13 % of the sediment > 1mm, and over 75 % < 0.1 mm. This is also true for sediments collected from the undeveloped well, with up to 93 % of the material < 0.1 mm. These sediments represent material that have migrated into the well and have been deposited during pumping only.

If a newly installed well is not developed before it is pumped, material from the well bore and fines from the pack, may be carried into the well when pumping is initiated. Developing the well will remove this material, but will not affect the volume or grain-size of fresh material that will then enter the well during normal operation.

7.6 Implications of field trial results

To help prevent the migration of fines from the waste to the borehole, a fine grained filter pack can be used. If the filter pack grading is based on the PSD of sediments that have been deposited in existing wells, the volume of sediment deposition will be reduced considerably. Alternatively, if the well is developed, a coarse gravel pack can been used, because the volume of sediment migration through a coarse-grained *developed* pack, is not significantly different than for wells with fine-grained *undeveloped* packs. The particle size of the material that is carried into the well will, however, be function of the filter pack size (developed or undeveloped).

Monitoring of TSS and material ingress has shown that the volume of sediment carried to a well is a function of the pumping regime, rather than the volume of leachate pumped or the filter pack grading used. The concentration of suspended sediments will be related to flow velocity into the well (especially at the start of pumping), before seepage faces have developed. This will result in high sediment concentrations at the start of pumping, and a rapid fall away to a more constant sediment load. Stop-start, and intermittent periods of pumping in leachate wells should therefore be avoided where possible. In low capacity wells, where drawdown will be rapid even at low extraction rates, pumps should not be installed at the base of the well. In this way, although it may not be possible to prevent rapid drawdown (indeed, drawdown to the pump inlet will be quicker), the change in flow velocity into the well will at least be minimised.

At Westbury, the alkali rich leachate and sulphate reducing conditions present in the landfill, inhibit microbial clogging (at least to an extent that would impair performance), and permit the use of fine-grained filter packs. The use of fine-grained packs in more typical methanogenic leachate, has yet to be proven. It is also acknowledged, that such a high proportion of fine-grained sediments at the test site (from the CKD waste) is unusual in a typical MSW landfill. Nevertheless, this emphasises the fact that wells should be designed on a site specific basis, and that no common design is suitable for all sites.

The field trials have demonstrated that using fine grained filter packs in landfill wells does not significantly reduce the volume of fines entering wells compared to wells with coarse gravel packs that have been developed. Developing wells can, however, significantly reduce the efficiency of the well due to the clogging of the pack during surging. The design of new leachate wells should, therefore, be based on individual site requirements, though a compromise may have to be made between well efficiency and preventing the deposition of material in the well, over time.

The long-term performance of fine-grained filter packs has yet to be proven in landfill. Until further research has been carried out on the clogging potential of fine-grained sands in high-strength leachate, new well installations should be installed with filters based on the recommendations for basal drainage aggregates (e.g. a minimum D_{10} of 10 mm (Paksy *et al.*, 1998)), unless leachate conditions exist that would permit the use of fine sands.

At the Westbury landfill, the requirement was for wells that did not clog with sediments. The wells were high yielding (owing to a large saturated depth), but the effective depth of the wells was reduced due to deposition of sediments. In this instance, developing existing wells would be recommended, and new wells should be installed with fine-grained packs. At the Rainham landfill discussed in Chapter 6, leachate yields from wells in the Phase 1 area were low, and significant sediment deposition had occurred in the wells. Further well development should be avoided, and new wells should be installed with coarse gravel pack with a minimum D_{10} of 10 mm. Pumping should be continuous, low volume, to prevent sudden drawdown's driving sediments into the wells.

7.7 Chapter Summary

New leachate extraction wells were installed at the Westbury landfill to investigate the applicability of using groundwater well selection rules and fine-grained filter packs in new landfill well installations. Each new well was completed with a different installation design; different well screen and filter pack. Laboratory tests investigating microbial well clogging suggested that it would be possible to use fine grained filter sands in the new well installations without the risk of clogging. The size grading of the filter packs used was determined based on PSD analysis of sediments recovered from existing wells, and rules used in groundwater well installation to prevent the migration of fines from the aquifer and pack to the screen. Three wells, completed with different screen and filter grades, were installed in two areas of the landfill. Observation wells were also installed, in each area, each with twin-level monitoring piezometers.

Short-term step-drawdown tests were carried out in two of the new wells, and an existing well that had previously been developed. The results of the pumping tests were analysed using the Hantush and Bierschenk (1963) methods. The tests show the aquifer loss calculated for each well to be similar, with little variability across the test area. There was, however, some difference in the calculated well losses between each well, with the undeveloped well, installed with the finest sand grade, showing the smallest amount of well loss overall. Similar loses were observed in two developed wells, one with a coarse gravel pack and one with a fine sand pack. The well losses calculated, are assumed to indicate clogging in the pack.

The effectiveness of the different well designs at preventing sediments from entering the well bore was assessed. Leachate samples were analysed for their TSS concentration, which was high at the start of pumping, but rapidly decreased by up to 50 % and remained constant for the duration of pumping. This is caused by high flow velocities into the well when pumps are first initiated, which rapidly decline as seepage faces develop along length the well screen. A laboratory settling test has also demonstrated that the concentration of SS in leachate sampled at the start of pumping (when SS are high) will be reduced, through settlement, by almost 50 % in static leachate. Intermittent pumping, where pumps are operated on a stop-go basis, may, therefore, be the prime casue of sediment ingress and deposition.

An estimation was made of the volume of sediment that has been deposited in the wells during pumping. When normalised against volume pumped, the volume of sediment deposition is similar in each well, with little difference between pack types. PSD analysis of sediments that had entered wells 36A and W36 during pumping, indicate that the grading of the sediments becomes finer with time.

The field trials have demonstrated that using fine grained filter packs in landfill wells does not significantly reduce the volume of fines entering wells compared to wells with coarse gravel packs that have been developed. The particle size of the material entering through the fine-grained pack, will however, be smaller. Developing wells can, however, significantly reduce the efficiency of the well due to the clogging of the pack during surging. New leachate wells should be designed on a site specific basis, and a compromise may have to made between well efficiency (i.e. well yield) and preventing the deposition of material in the well over time.

Chapter 8

Discussion and implications for practice

8.1 Introduction to chapter

Field trials and archival landfill well data have been used to investigate the problems associated with, and the limitations of, using vertical wells for leachate extraction in landfills. The known problems of microbial clogging in basal drainage systems and the low hydraulic conductivity of waste have been investigated, and how these may effect the performance of vertical wells over time. Techniques commonly used in the groundwater industry have been used in the design of new landfill wells, to help maximise yields, reduce clogging and to remediate existing wells. Field tests have compared different well designs and installation methods, and the performance of wells has been assessed using hydrogeological pumping tests.

The results and discussions from previous chapters will be used to suggest what implications the research may have for the design of new wells and remediation of new and existing wells. From this, conclusions will be drawn as to the best available techniques of installing and maintaining vertical wells in landfill. The research has been predominantly UK focused. The application of the research in a wider context will be discussed, and recommendations for future research will be made.

8.2 Installation, operation and maintenance

The wells examined in the database of existing leachate extraction wells, demonstrate that although some variation does exist in leachate well design, the majority of wells are installed using similar techniques and materials: rotary barrel auger drilling, installed with a steel well screen with torch-cut slots, with a coarse gravel pack. Where variations in design do exist, these do not appear to be attributable to the local waste characteristics and may not always be due to site specific design needs. Based on a review of published investigations, field trials and standard practice, a summary of the research findings and the implications for new well design, installation, operation and maintenance is given below.

8.2.1 Installing new wells in landfill

Four different borehole drilling methods were discussed: rotary open-hole, rotary barrel-auger, continuous flight auger and fully-cased hammer-driven. Each method was found to have advantages and disadvantages in terms of installation. The rotary barrel-auger drilling technique was found to be the most capable for penetrating all waste types, creating vertical, straight sided boreholes. The method also allowed the accurate logging of the waste. When drilling through saturated waste, it may be difficult to remove the waste core from the well, which can collect in the bottom of the borehole, restricting the installation depth and contaminating the liner. Continuous flight auger drilling methods are more rapid that rotary barrel auger methods, though accurate logging of the waste is not possible and loss of arisings may also occur when drilling through saturated horizons. A flight auger borehole may also deviate somewhat from the vertical when compared to a barrel augured well.

Rotary open-hole methods are not suitable for general landfill well drilling, and fully-cased hammer driven techniques are yet to be proved in landfill. Logging of the waste is not possible using either of these methods.

Observations made during well exhumations and during the installation of new wells, suggested that barrel auger drilling could result in a well skin of smearing and ground waste around the borehole due to the action of the auger. Pumping tests have demonstrated, that the well loss through the skin will be small and no greater than wells installed using flight auger methods. Wells installed using rotary-open hole methods may have greater well losses due to the compaction of waste in the borehole walls during drilling. At the low flow rates generally associated with landfills, the head loss due to formation damage by any drilling method is relatively small.

Further considerations when selecting a drilling method for new wells, may include safety, cost and availability of plant. These were not investigated in this study.

Wells should be installed with a filter pack and a well screen that compliments the filter pack grading. The choice of filter pack should be based in part on the PSD of the waste, and in part on the leachate chemistry at a given site. If sulphate reducing conditions are the predominant biodegradation processes, or in old landfills were the biological loading is significantly reduced (Rowe and Nadarajah, 1996), fine-grained filter packs can be used without the risk of microbial clogging. The pack size can be selected from the finest PSD grading of the waste, where:

$D_{15\text{filter}} \quad 5 \times D_{85\text{aquifer}}$

Accurately determining the PSD of the waste at a given site can be complicated by the heterogeneity of MSW, which may include a wide range of particles sizes, and because representative samples will be difficult to collect. Where existing wells have had significant sediment migration, an estimation of the PSD of the fines content of the waste can be made. The use of fine-grained packs in new landfills and those exhibiting late stage 3 and early stage 4 acetogenic and methanogenic degradation phases, has yet to be proven. Based on analysis of basal drainage aggregates (e.g. Paksy *et al.*, 1998), a filter pack with a $D_{10\text{filter}}$ size of at least 10 mm is therefore recommended.

Well screen materials were not discussed in this research, but the screen slot type and dimension, should be chosen to compliment the filter pack whether steel or plastic well screens are used. At the low flow rates associated with landfill wells, the choice of open area is perhaps less important as well losses will be minimal even if the screen becomes clogged. The well screen slot opening size should, therefore, be selected to retain the filter pack using the following rule:

well slot size = $D_{10\text{filter}}$

New wells should not be developed after installation. Although some debris (i.e. ground waste and soils) from the drilling process may collect in the borehole during installation, developing wells can cause fine grained material from the waste to invade the pack. This will reduce the permeability of the pack, and may also block flow paths to the well from upper horizons of waste. Drilling trials have shown, that the head loss through the well skin caused through installation is insignificant.

8.2.2 Operating wells

Clogging mechanisms in landfill wells may be physical, chemical or biological. Clogging can occur in the well bore, the screen, filter pack and waste around the well, though only physical clogging of the filter pack and well bore will significantly affect a well's performance.

Exhumations and down-well CCTV surveys have shown that the clogging potential of vertical well screens is high in the gas zone above the leachate table. Where present, precipitates and oxidation products may completely occlude screen openings. In the leachate zone, in the pumped part of the well, the risk of clogging is low and will not adversely affect well performance. Where clogging does occur below the leachate level, analysis suggests that even if slots are almost completely closed, at low entrance velocities, head loss through the screen will be minimal (Powrie and Beaven, 2003).

Over time, the corrosion of steel well screens may lead to a reduction in the structural integrity of the well. Significant reductions (up to 7 mm) in casing section were noted in exhumed well screens.

Physical clogging is the most significant clogging mechanism in vertical wells. The reduction in material permeability by the redistribution of particulate matter will affect the well, filter pack and waste directly around the well. The migration of fines to a well will occur during pumping and if wells are developed, and is related to flow velocities into the well. Two processes have been identified. When a well is first pumped after a period of quiescence, there will be an initial flush of sediment laden leachate due to high flow velocities in the upper parts of the well and turbulence in the well bore. After a short period of pumping, seepage faces will develop in the borehole, flow rates will stabilise and distribute along the wetted length of the well. As flow rates drop, the amount of suspended material carried to the well will decline to a background constant. The concentration and particle size of suspended solids will be a function of the flow velocity, and therefore the pumping rate. The higher the rate of pumping, the greater the radial distance from the well over which fines may be mobilised.

To help prevent high flow velocities and the resultant migration of fines, pumping should be continuous, with initially low well yields, to prevent sudden drawdown in the well. Stop-start, intermittent pumping where the leachate in storage in the well is rapidly removed, and pumps switch off during recharge, should be avoided. In low capacity wells, where drawdown will be rapid even at low extraction rates, pumps should not be installed at the base of the well.

The nature of the sediments entering wells will be small pieces of fresh waste, degrading waste, intermediate cover soils and debris from the drilling of the borehole.

8.2.3 Maintaining and remediation wells

Sedimentation in landfill wells is common due to the fine-grained nature of degrading waste and intermediate cover soils. Fine-grained filter packs can generally not be used because of the risk of microbial clogging. Preventing fine, particulate matter migrating to wells during pumping, may therefore not be possible, and a certain amount of sedimentation in wells over time should be expected.

Well bore deposits restrict pump installation and will reduce the effective depth of the well. Well rehabilitation development, using surge and bail or overpumping techniques, can successfully remove deposited sediments and lost items from inside wells. The high fluid velocities created during development may lead to the invasion of the pack by soils and fine waste that would otherwise not be carried to the well during normal operation. This will result in a reduction in permeability, and may adversely affect the performance of the well. Well rehabilitation development is therefore not recommended in landfill wells where fine-grained intermediate cover soils or wastes are present.

8.3 Conclusions of research

The processes leading to clogging, encrustation and performance deterioration of a landfill dewatering system are many, the evidence for such has been widely researched. However, these studies often only consider the failure or deterioration of under-lying drainage systems, not vertical well fields, and generally only document the evidence and processes of failure. Few remediation or preventative measures are suggested. In older landfills, where no basal containment liner and leachate collection system is present or has failed, vertical wells may be the only economical option for leachate management.

Down hole CCTV surveys of leachate wells have shown that chemical precipitations are common, often completely coating the well screen and closing all slots. This was also observed during well exhumation works. However, precipitates were generally only present in the gas zone, above the leachate table, where the closure of slots will not attribute to well losses affecting the flow of leachate to the well. This was true also of microbial deposits observed in the gravel filter pack, which were only present above the leachate table.

Smearing of ground waste and cover soils around the borehole was observed in the wells exhumed. The wells were drilled using a rotary barrel-auger, which is the most common method of landfill well installation. Field trials investigating different drilling techniques have shown that the well losses associated with drilling are, however, small.

Over time, sediments and waste pieces may be washed into the well or suspended within the leachate flowing to the pump. Some of this material will be deposited in the well. Accumulations of sediment, will, over time, reduce the available drawdown in the well, and particles of waste and sediment may cause premature wear to the pumping infrastructure.

When designing new wells for use in a landfill, a compromise may have to be made between an ideal well design to limit well losses, a design that filters fine-grained material from being washed into the well, and one that is not prone to microbial clogging. Rules used in the groundwater industry for selecting filter packs and well screens, may, therefore, not be suitable for the design of landfill wells. If a well does become clogged with deposited sediments, then well development techniques should be avoided, as this may lead to further clogging.

The long-term performance of landfill wells will ultimately be restricted by the low hydraulic conductivity of waste and the amount of fines in the waste. Site specific well designs may, therefore, not necessarily improve well yields, as it is flow to the well that is the limiting factor, not the design of the well. However, by designing wells that will reduce the likelihood of microbial and physical clogging, and operating wells in a way that will reduce the amount of fines migrating to the borehole, the operating life of a well may be extended considerably.

8.4 Application of results

The research can be applied, in a practical sense, to the operation and design of leachate management systems in current and new landfill sites. The study has produced new evidence that fine grained particulate matter, particularly from intermediate cover soils, is responsible for the decline in performance of leachate extraction wells over time and is the main limiting factor in well operation. The findings have exposed the limitations of current well design, and although there is no ideal design for new well installations, the results can be used to improve the construction and operational regimes of future leachate extraction points.

The research discussed in this thesis, is based on the field testing of new and existing landfill wells, and from archival landfill data. The limitations of field-based research from just a small number of UK based sites are acknowledged: waste is inherently heterogeneous making comparisons between wells at different sites, and even within the same site, difficult. Where practicably possible, a range of well designs and landfill types have been included, though when comparing the performance of individual wells, the test parameters have been kept the same (e.g. waste depth, operational strategy, though waste age and composition, and saturated depth may vary somewhat between the test sites).

The results are considered to be applicable in the more general field of water table control, because the controlling factors are the same in any landfill that contains fine grained, unconsolidated material. Therefore, where soils are used as cover material, or if there is a high fines content, the research findings will apply. External influences, such as temperature and rainfall, and the composition of different MSW wastes, will not adversely affect the performance of a well, though in warmer climates, the rate of biodegradation will be significantly quicker (Robinson, 2005).

The direct beneficiaries from this work will be those conducting field installations and numerical simulations aimed at improving landfill management practices, and in the design and operation of existing and future well fields. If vertical leachate extraction wells are to be considered a viable, long-term means of leachate management, then improvements in waste placement techniques and site operations which will enhance fluid flow and waste degradation should be adopted. The current trend of using fine-grain, low permeability soil as an intermediate cover material should be avoided, and in so doing, the long term performance of wells may be improved, and well development of new and failing wells may be a viable option.

8.5 Recommendations for further research

8.5.1 Filter packs

Different filter sand grades have been investigated in laboratory and landfill installations. In the short term, no significant differences were noted in the effectiveness of the wells to prevent material ingress. Repeat pumping tests of field wells should be carried out to determine the effects of microbial clogging and sediment clogging within the different filter grades over time.

8.5.2 Well development

Monitored leachate yields from individual wells did not indicate that there had been any improvement in performance following well development. In many of the wells, yields fell following development. Fully instrumented well performance tests should be carried out in un-pumped wells before, directly following and some time after well development to determine the effects of well development on well performance.

Small scale well development tests using laboratory apparatus should be carried out to determine the affects and area of influence of well development in different parts of a well: the screen, pack and waste, and the effects of development on different pack grades.

8.5.3 The effects of landfill gas

The affects of landfill gas on the drainable porosity of aggregates have been investigated in laboratory clogging trials (e.g. Nikolova, 2004). Gas bubbles will reduce the hydraulic conductivity of waste by blocking flow paths through the waste and decreasing the size of the water conducting pores (Hudson *et al.*, 2001). Fully instrumented pumping tests in sealed leachate wells should be carried out to monitor the production and affects of landfill gas on leachate well performance.

8.5.4 The affect of well screen clogging in landfill gas wells

Down-well CCTV surveys of leachate extraction wells have shown that the formation of precipitates and the occlusion of well screen apertures in the gas zone above the leachate table are common, though will not effect the performance of the well. In landfill gas extraction wells, however, the plugging of screen apertures in the gas-zone would be undesirable for long-term gas yields, and, over time, as the screen clogs, precipitates may impair the performance of the well. Further research in to gas-well performance, including long-term field surveys and numerical modelling, is recommended.

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Appendix A

Vertical well data base

ID	Location	Company	Well No	County	Waste Types	Approx Age of Waste
1	Kibblesworth	NEM	LW3A	Northumbria	MSW & some fly ash	
2	Kibblesworth	NEM	LW7A	Northumbria	MSW & some fly ash	
3	Warnham	Cleanaway	201 concr sleeve	W Sussex	MSW, Ind, Comm, Asbestos	
4	Warnham	Cleanaway	202 concr sleeve	W Sussex	MSW, Ind, Comm, Asbestos	
5	Warnham	Cleanaway	205 concr sleeve	W Sussex	MSW, Ind, Comm, Asbestos	
6	Warnham	Cleanaway	206 concr sleeve	W Sussex	MSW, Ind, Comm, Asbestos	
7	Warnham	Cleanaway	207 concr sleeve	W Sussex	MSW, Ind, Comm, Asbestos	
8	Warnham	Cleanaway	WAR211	W Sussex	MSW, Ind, Comm, Asbestos	
9	Warnham	Cleanaway	WAR218	W Sussex	MSW, Ind, Comm, Asbestos	
10	Warnham	Cleanaway	WAR219	W Sussex	MSW, Ind, Comm, Asbestos	
11	Calvert	SME	D6	Bucks	Old (15yrs) MSW	
12	Calvert	SME	F67	Bucks	75% MSW, 25% ?	
13	Calvert	SME	C32	Bucks	75% MSW, 25% ?	
14	Calvert	SME	B21	Bucks	Old MSW, 75% MSW, 25% ?	
15	Calvert	SME	D8	Bucks	Old (15yrs) MSW	
16	L'Field	SME	DB19	Beds	MSW & some hazardous liquids	
17	L'Field	SME	UE7	Beds	MSW & some hazardous liquids	
18	L'Field	SME	UH2	Beds	MSW & some hazardous liquids	
19	L'Field	SME	UH12	Beds	MSW & some hazardous liquids	
20	L'Field	SME	DB20	Beds	MSW & some hazardous liquids	
21	L'Field	SME	GD9	Beds	MSW & some hazardous liquids	< 1987
22	L'Field	SME	A1-4	Beds	MSW & some hazardous liquids	< 1987
23	L'Field	SME	C3	Beds	MSW & some hazardous liquids	1987 - 90
24	Mountsorrel	Cleanaway	MOU204*	Leicestershire	Quarry dust	
25	Mountsorrel	Cleanaway	MOU205	Leicestershire	MSW	
26	Mountsorrel	Cleanaway	MOU213	Leicestershire	MSW	
27	Mountsorrel	Cleanaway	MOU238	Leicestershire	MSW	
28	Mountsorrel	Cleanaway	MOU257	Leicestershire	MSW	
29	Mountsorrel	Cleanaway	MOU258	Leicestershire	MSW	
30	Mountsorrel	Cleanaway	MOU757	Leicestershire	MSW	
31	Whites Pit	Biffa	DWS2M	Dorset	MSW	
32	Whites Pit	Biffa	DCC2M	Dorset	MSW	
34	Pluckley	Cleanaway	PLU226	Kent	MSW	
35	Pluckley	Cleanaway	PLU227	Kent	MSW	
36	Pluckley	Cleanaway	PLU228	Kent	MSW	
37	S.Ockendon	Cleanaway	OCK260	Essex	MSW & some asbestos	
38	S.Ockendon	Cleanaway	OCK261	Essex	MSW & some asbestos	

ID	Location	Company	Well No	County	Waste Types	Approx Age of Waste
39	S.Ockendon	Cleanaway	OCK269	Essex	MSW & some asbestos	
40	Rainham	Cleanaway	RAI613*	Essex	Ash, gravel, cinders	
41	Rainham	Cleanaway	RAI614*	Essex	Ash, gravel, cinders	
42	Rainham	Cleanaway	RAI615*	Essex	Ash, gravel, cinders	
43	Rainham	Cleanaway	RAI616*	Essex	Ash, gravel, cinders	
44	Rainham	Cleanaway	RAI617*	Essex	Ash, gravel, cinders	
45	Rainham	Cleanaway	RAI620*	Essex	Ash, gravel, cinders	
46	Warnham	Cleanaway	WAR203	W.Sussex	MSW, Ind, Comm, Asbestos	
47	Choppington	Cleanaway	CHO219	Northumberland		
48	Mountsorrel	Cleanaway	MOU336	Leicestershire	MSW	
49	Bletchley	SME	A22	Bucks	MSW	1990 - 93
50	Bletchley	SME	A23	Bucks	MSW	1990 - 93
51	Calvert	SME	A15	Bucks	MSW	1985 - 88
52	Calvert	SME	C30	Bucks	MSW	1985 - 88
53	Calvert	SME	C24	Bucks	MSW	1982 - 85
54	Calvert	SME	AWA1	Bucks	MSW	1980 - 84
55	Westbury	Viridor	WB010LM	Wiltshire	CKD with some MSW	
56	Westbury	Viridor	WB013LM	Wiltshire	CKD with some MSW	
57	Westbury	Viridor	WB031LM	Wiltshire	CKD with some MSW	
58	Westbury	Viridor	WB032LM	Wiltshire	CKD with some MSW	
59	Westbury	Viridor	WB035LM	Wiltshire	CKD	
60	Westbury	Viridor	WB036LM	Wiltshire	CKD	
61	Rainham	Cleanaway	RAI717	Essex	MSW	
62	Rainham	Cleanaway	RAI718	Essex	MSW	
63	Rainham	Cleanaway	RAI727	Essex	MSW	
64	Rainham	Cleanaway	RAI728	Essex	MSW	
65	Rainham	Cleanaway	RAI731	Essex	MSW	
66	Rainham	Cleanaway	RAI732	Essex	MSW	
67	Rainham	Cleanaway	RAI736	Essex	MSW	
68	Hill and More	Mercia Waste Ltd	LC1	Worcestershire	MSW	
69	Hill and More	Mercia Waste Ltd	LC3	Worcestershire	MSW	
70	Hill and More	Mercia Waste Ltd	LC4	Worcestershire	MSW	
71	Hill and More	Mercia Waste Ltd	LC5	Worcestershire	MSW	
72	Hill and More	Mercia Waste Ltd	LC6	Worcestershire	MSW	
73	Hill and More	Mercia Waste Ltd	LC7	Worcestershire	MSW	
74	Hill and More	Mercia Waste Ltd	LC8	Worcestershire	MSW	
75	Hill and More	Mercia Waste Ltd	LC9	Worcestershire	MSW	
76	Hill and More	Mercia Waste Ltd	LC10	Worcestershire	MSW	

ID	Waste Depth (m)	Good/Poor well	Installation Date	Age (months)	Borehole drilled depth (m)	Current depth (m)	Drilling Method
1	28.00	good	01/11/1998	5	25.00	25.00	Cable Percussion
2	28.00	good	01/11/1998	5	25.00	25.00	Cable Percussion
3	25.40	good	05/08/1994	54	25.10	25.40	Rotary (barrel auger)
4	31.00	poor				30.72	
5	24.00	poor (A j-test)				24.00	
6	22.00	good	1994/95	48		21.50	
7	23.00	average (G j-test)				22.59	
8		average				31.85	Pit dug with grab line
9		average (G j-test)	25/08/1994	54	20.20	20.19	Rotary (barrel auger)
10		poor	22/08/1994	54	23.30	23.27	Rotary (barrel auger)
11	14.00	good			10.50		Rotary (barrel auger)
12			01/11/1998	5			Rotary (barrel auger)
13	15.00	good	01/11/1998	5	14.20	14.20	Rotary (barrel auger)
14	22.00	good	1990-91	90	20.15	19.40	Rotary (barrel auger)
15	17.00	poor			11.46		
16		good	28/02/1997	25	26.50	23.60	
17		good	11/01/1996	38	27.00	?	
18		good	23/09/1996	30	16.00	?	
19		poor	27/09/1996	30	18.50	?	
20		poor	25/02/1997	25	23.60	?	
21			29/07/1994	54		16.20	
22			31/09/94	52		14.50	
23			not known			13.35	
24	35.00	v.good*	03/06/97?	22	25.00		
25	50.00	good	03/06/97?	22	30.50		
26	25.00	good	23/02/1995	50	25.00		Rotary (barrel auger)
27	40.00	poor	05/12/1996	28	35.52		Rotary (barrel auger)
28	35.00	poor	30/08/1997	20	30.00		Rotary (barrel auger)
29	35.00	poor	29/08/1997	20	30.00		Rotary (barrel auger)
30	50.00	good	03/06/97?	22	28.20		Rotary (barrel auger)
31	50.00	new well	20/03/1999	1			Rotary (barrel auger)
32	50.00	new well	20/03/1999	1	34.50		Rotary (barrel auger)
34		poor	25/09/1998	6	10.50		Rotary (barrel auger)
35		poor	01/10/1998	6	13.30		Rotary (barrel auger)
36		poor	22/08/1998	6	17.60		Rotary (barrel auger)
37		good				7.67	
38		good				16.78	

ID	Waste Depth (m)	Good/Poor well	Installation Date	Age (months)	Borehole drilled depth (m)	Current depth (m)	Drilling Method
39		good				19.85	
40							
41	10.00		April 1998	12	9.00	9.00	Cable percussion
42	10.00		April 1998	12	8.00	8.00	Cable percussion
43							
44							
45							
46		poor	04/08/1994	56	27.40		Rotary (barrel auger)
47							
48	35.00	poor	06/04/1998	12	31.00		Rotary (barrel auger)
49			27/10/1995	42	20.70	not rodded	
50			24/10/1995	42	23.40	not rodded	
51			10/08/1994	56	18.00	17.75	
52			17/05/1994	59		17.90	
53			01/08/1995	42		19.05	
54			1984	56		not known	
55		Poor	1994	60	14.38	13.36	Flight Auger
56		Poor	1994	60	7.38	4.18	Flight Auger
57		Poor	Oct-98	5	36.10	26.14	Flight Auger
58		Poor	Oct-98	5	35.00	28.42	Flight Auger
59		Good	Oct-98	5	24.00	12.17	Flight Auger
60		Good	Oct-98	5	24.09	24.06	Flight Auger
61	19.00		26/06/1995	70	20.00	15.65	Rotary (barrel auger)
62	20.00		27/06/1995	70	21.33	17.09	Rotary (barrel auger)
63	20.40		05/07/1995	70	20.78	20.00	Rotary (barrel auger)
64	21.90		04/07/1995	70	22.00	21.65	Rotary (barrel auger)
65	19.30		06/07/1995	70	19.62	18.90	Rotary (barrel auger)
66	19.00		04/07/1995	70	21.00	17.42	Rotary (barrel auger)
67	15.90		08/07/1995	70	16.31	14.95	Rotary (barrel auger)
68	10.00	Low	Jun-95	84	9.50		Flight Auger (375 mm)
69	9.00	High	Jul-95	84	8.50	5.9	Flight Auger (375 mm)
70	8.00	High	Aug-95	84	7.50	5	Flight Auger (375 mm)
71	10.25	Low	Sep-95	84	9.75	7.75	Flight Auger (375 mm)
72	10.50	High	Oct-95	84	10.00		Flight Auger (375 mm)
73	10.40	Low	Nov-95	84	9.90		Flight Auger (375 mm)
74	10.25	Low	Dec-95	84	9.75	7.75	Flight Auger (375 mm)
75	10.30	High	Jan-96	84	9.80		Flight Auger (375 mm)
76	11.00	Low	Feb-96	84	10.50	8.5	Flight Auger (375 mm)

ID	Casing OD (mm)	Casing Type	Casing Length (m)	Screen Type	Screen Length (m)	% Open Area	Slot Dimensions (mm)
1	200	HDPE	15.00	vertical slots HDPE	9		3-5 wide
2	200	HDPE	15.00	vertical slots HDPE	9		3-5 wide
3	178 (7")	Steel	5.00	torch cut vertical slots	20		0
4	178 (7")	Steel	0.00	torch cut vertical slots	0		
5	178 (7")	Steel	0.00	torch cut vertical slots	0		1
6	178 (7")	Steel	0.00	torch cut vertical slots	0		
7	178 (7")	Steel	0.00	torch cut vertical slots	0		
8	178 (7")	Steel	0.00	torch cut vertical slots	0	3-4	10 * 100
9	178 (7")	Steel	5.00	torch cut vertical slots	15	3-4	10 * 100
10	178 (7")	Steel	0.00	torch cut vertical slots	0	3-4	10 * 100
11	200	HDPE	0.00	horizontal slots HDPE	0		3 * 155
12			0.00		0		
13	225	HDPE	0.00	perforations HDPE	0		11mm dia
14	200	HDPE	0.00	horizontal slots HDPE	0		
15	300	HDPE	0.00	horizontal slots HDPE	0		
16			5.00		21		
17	200		6.00		18		
18	200		6.00		9		
19	200		9.00		9		
20			5.00		18		
21	160	MDPE	6.00		12	20	3 * 170
22	160	MDPE	6.00		11	20	3 * 170
23	160	MDPE	not known		not known	20	3 * 170
24	610	Steel	3.00	torch cut vertical slots	22		
25		Steel	0.00	torch cut vertical slots	0	3-4	10 * 100
26	178 (7")	Steel	7.00	torch cut vertical slots	18	3-4	10 * 100
27	128 (5")	Steel	6.00	torch cut vertical slots	24	3-4	10 * 100
28	140 (5.5")	Steel	3.80	torch cut vertical slots	9	3-4	10 * 100
29	140 (5.5")	Steel	3.80	torch cut vertical slots	14	3-4	10 * 100
30	178 (7")		0.00		0		
31		Steel	0.00	torch cut vertical slots	0		? * 300
32		Steel		torch cut vertical slots	0		? * 300
34	140 (5.5")	Steel	4.00	torch cut vertical slots	9	3-4	10 * 100
35	140 (5.5")	Steel	4.00	torch cut vertical slots	9	3-4	10 * 100
36	140 (5.5")	Steel	4.00	torch cut vertical slots	9	3-4	10 * 100
37			0.00		0		
38			0.00		0		

ID	Casing OD (mm)	Casing Type	Casing Length (m)	Screen Type	Screen Length (m)	% Open Area	Slot Dimensions (mm)
39			0.00		0		
40			0.00		0		
41			0.00	torch cut vertical slots	0	3-4	10 * 100
42			4.00		5		
43			4.00		6.5		
44			0.00	torch cut vertical slots	0	3-4	10 * 100
45			0.00	torch cut vertical slots	0	3-4	10 * 100
46	178 (7")	Steel	6.00	torch cut vertical slots	21	3-4	10 * 100
47					0		
48	127 (5")	Steel	15.00	torch cut vertical slots	9	3-4	10 * 100
49	200	MDPE	4.56			20	3 * 170
50	200	MDPE	4.79			20	3 * 170
51						20	
52						20	
53						20	
54						not known	
55	150	MDPE		Cut vertical slots			
56	150	MDPE		Cut vertical slots			
57	150	Steel		torch cut vertical slots			
58	150	Steel	0.00	torch cut vertical slots			
59	150	Steel	0.00	torch cut vertical slots			
60	150	Steel	0.00	torch cut vertical slots			
61	178	Steel	6.50	torch cut vertical slots	13.50	3-4	10 * 100
62	178	Steel	7.25	torch cut vertical slots	14.08	3-4	10 * 100
63	178	Steel	6.00	torch cut vertical slots	14.78	3-4	10 * 100
64	178	Steel	5.00	torch cut vertical slots	17.00	3-4	10 * 100
65	178	Steel	5.70	torch cut vertical slots	13.92	3-4	10 * 100
66	178	Steel	6.00	torch cut vertical slots	15.00	3-4	10 * 100
67	178	Steel	4.50	torch cut vertical slots	11.81	3-4	10 * 100
68	150	HDPE	2.0		8.00		
69	150	HDPE	2.0		7.00		
70	150	HDPE	2.0		6.00		
71	150	HDPE	2.0		8.25		
72	150	HDPE	2.0		8.50		
73	150	HDPE	2.0		8.40		
74	150	HDPE	2.0		8.25		
75	150	HDPE	2.0		8.30		
76	150	HDPE	2.0		9.00		

ID	Filter Pack Type	FP Thickness (mm)	Development Type	Dipped static water level (m)
1	10mm rounded gravel	50	screen jetted with clean water & airlifted	12.1
2	10mm rounded gravel	50	screen jetted with clean water & airlifted	12.32
3	brick rubble (20mm shingle)	722		48 mAOD
4	brick rubble	722		47 mAOD
5	brick rubble	722		44 mAOD
6	brick rubble	722		44 mAOD
7	brick rubble	722		51 mAOD
8		0		48 mAOD
9	20mm shingle	0		51 mAOD
10	20mm shingle	0		52 mAOD
11		0		0
12		0		8
13	40mm gravel	0	No development	7.5
14	20mm gravel	0	flushed out	0
15		0		0
16		0		0
17		0		0
18		0		0
19		0		0
20		0		0
21		0		
22		0		
23		0		
24		0		0
25	20mm shingle	0		27.4
26	20mm shingle	90		0
27	20mm shingle	0		0
28	20mm shingle	82		23.2
29	20mm shingle	82		21.1
30		0		25
31		0	Not developed	0
32		0	Not developed	0
34	40mm shingle	80	Not developed	0
35	40mm shingle	80	Not developed	0
36	40mm shingle	80	Not developed	0
37		0		5.56
38		0		6.33

ID	Filter Pack Type	FP Thickness (mm)	Development Type	Dipped static water level (m)
39		0		10.45
40		0		0
41		0		0
42		0	Airlift pumping and surging	0
43		0	Airlift pumping and surging	3.5
44		0		0
45		0		0
46	20mm shingle	0		
47		0		
48	20mm shingle	65		
49	20mm gravel	50	unsure	9.05
50	20mm gravel	50	unsure	11.84
51		0		
52		0		
53		0		
54		0		
55	5mm gravel	0	Shell and augur bailing	4.96
56	5mm gravel	0		3.2
57	5mm gravel	0	Shell and augur bailing	9.17
58	5mm gravel			9.52
59	5mm gravel			
60	5mm gravel			
61	20mm shingle	89	Shell and augur bailing	
62	20mm shingle	89		
63	20mm shingle	89		
64	20mm shingle	89		
65	20mm shingle	89		
66	20mm shingle	89	Shell and augur bailing	
67	20mm shingle	89		
68	Gravel (unspecified)	112.5	No development	
69	Gravel (unspecified)	112.5	No development	
70	Gravel (unspecified)	112.5	No development	
71	Gravel (unspecified)	112.5	No development	
72	Gravel (unspecified)	112.5	No development	
73	Gravel (unspecified)	112.5	No development	
74	Gravel (unspecified)	112.5	No development	
75	Gravel (unspecified)	112.5	No development	
76	Gravel (unspecified)	112.5	No development	

ID	Dipped pumped level (m)	Drawdown (m)	Maximum yield (m3/day)	Average flow rate (m3/d)	Saturated thickness (m)	Jug test (m3/d)
1	14.68	2.58	57.9	51.8		NA
2	17.42	5.10	61.3	59.3		NA
3	45 mAOD	3.50				10.3
4	39 mAOD	8.00				0.1
5	41 mAOD	3.00				3.4
6	38 mAOD	6.00				17.3
7	47 mAOD	4.00	3.43	0.71		15.4
8	39 mAOD	9.00				3.6
9	48 mAOD	3.00	5.14	0.86		16.1
10	48 mAOD	4.00	2.14	0.57		2.3
11	0					
12	16.95	8.95	11.3			
13	7.5	0.00		7		59.07
14	0		3.7	2.4		
15	0					
16	12.48		23.68	10.18		NA
17	8.97		15.67	4.81		NA
18	7.12		29.78	8.32		NA
19	?		2.54	0.63		NA
20	?		9.59	6.8 originally 1.0 now		NA
21			4.3			NA
22			50.4			NA
23			8.6			NA
24	0					
25	31.78	4.38				
26	27.25					
27	34.85					
28	26.6	3.40				
29	27.71	6.00				
30	30.45	5.45				
31	0					
32	0					
34	0					
35	0					
36	0					
37	0			33.0 approx		
38	0			33.0 approx		

ID	Dipped pumped level (m)	Drawdown (m)	Maximum yield (m3/day)	Average flow rate (m3/d)	Saturated thickness (m)	Jug test (m3/d)
39	0			33.0 approx		
40	0					
41	0					NA
42	0			3.0		NA
43	0		43	14.5		NA
44	0					NA
45	0					
46						
47						
48						
49			6			NA
50			13.7			NA
51			2.4			NA
52			5.3			NA
53			5.8			NA
54			5			NA
55						
56						
57						
58						
59						
60						
61	14.24		3.54	0.42	3.5	
62	16.14		1.09	0.34	2.33	
63	19.02		1.23	0.35	1.28	
64	21.94		2.10	0.15	2	
65	17.86		1.61	0.4	1.62	
66	16.85		1.14	0.26		
67	14.01		0.71	0.16	12.3	
68				0.15		
69				1.5		
70			3.00	1.5		
71			0.50	0.15		
72			3.00	1.5		
73			0.10	0.15		
74			0.10	0.15		
75			1.18	0.15		
76			<0.03	0.15		

ID	Pump Type	Pump capacity (m3/d)	Pump depth (m)	Comments
1	electric submersible			installed in area of high permeability
2	electric submersible			installed in area of low permeability
3	Solo	9		
4	Solo	9		
5	Solo	9		
6	Solo	9		
7	Solo	9		
8	Solo	9		
9	Air injection			
10	Solo	9		
11	LOWRA electric		12	
12			21	
13	CAPRARI ? Electric		13	low part of site (acts as sump = lots of leachate)
14	electric		18	pump always in good condition
15				
16	MGS		23	
17	Air forced			pump currently stuck
18	Solo	9		pump currently stuck
19	Solo	9		pump currently stuck
20	?			unrepresentative as concrete sump (v.g Q data)
21	submersible hydrainer			
22	submersible hydrainer			
23	submersible hydrainer			
24				tar problem (congeals on cooling) See WP photos
25	Eductor		30	tar problem (congeals on cooling) See WP photos
26	Eductor		22	tar problem (congeals on cooling) See WP photos
27	Eductor			tar problem (congeals on cooling) See WP photos
28	Eductor			tar problem (congeals on cooling) See WP photos
29	Eductor			tar problem (congeals on cooling) See WP photos
30	Eductor		28	tar problem (congeals on cooling) See WP photos
31	B & M air			new well - silting up already
32	B & M air			new well - silting up already
34				
35				
36				
37				
38				

ID	Pump Type	Pump capacity (m3/d)	Pump depth (m)	Comments
39				
40				
41				
42	electric submerisble		8	
43	electric submerisble			good initial yield drops off dramatically to 0.05
44				
45				
46				
47				
48				
49	submersible hydrainer		17	
50	submersible hydrainer			
51	submersible hydrainer			
52	submersible hydrainer			
53	submersible hydrainer			
54	submersible hydrainer			
55				
56				
57				
58				
59				
60				
61	Educter / pneumatic			
62	Educter / pneumatic			
63	Educter / pneumatic			
64	Educter / pneumatic			
65	Educter / pneumatic			
66	Educter / pneumatic			
67	Educter / pneumatic			
68	Pneumatic			
69	Pneumatic			
70	Pneumatic			
71	Pneumatic			
72	Pneumatic			
73	Pneumatic			
74	Pneumatic			
75	Pneumatic			
76	Pneumatic			

Appendix B

CCTV Survey

&

Well exhumation

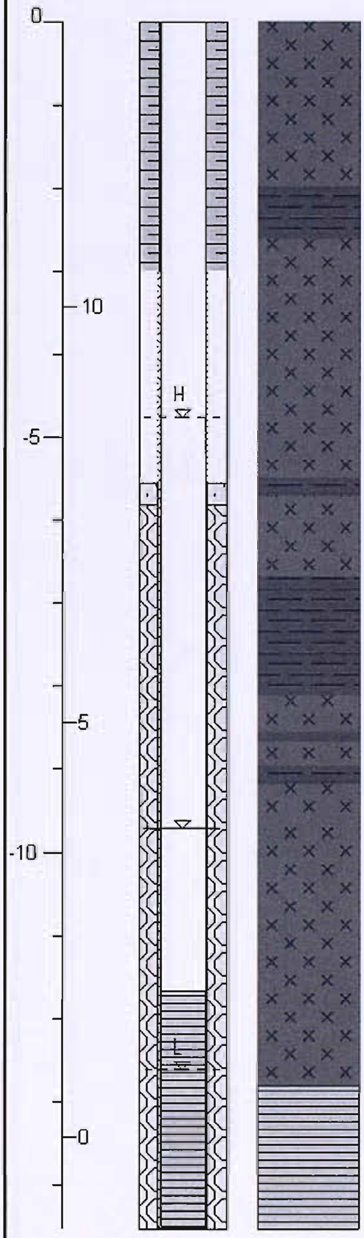
	Site	Well No.	Well installed	Date of survey	Screen type	Leachate level (mBCT)	Base level (mBCT)	Estimated % of slot clogging	Observations
9	Rainham	328	1998	06/03/2002	Steel	13.1	15.78	0	Some staining in upper well. All slots open to leachate level. Can not see below.
10	Rainham	375	1998	06/03/2002	Steel	30.66	31.66	0 - 80	Some foam in well. Slots directly within leachate fully open. Some degree of clogging encrustations in upper well - 5 to 80 %.
11	Rainham	382	1998	06/03/2002	Steel		5.1	n/a	Blockage at 5.10 m. Much foam in well. No slots above blockage, but no encrustations visible.
12	Rainham	384	1998	2002	7" Steel			n/a	Casing blocked with waste at 4 mBCT. Some surface deposits.
13	Rainham	387	1998	06/03/2002	7" Steel	17.76	27.19	100	Directly above leachate level and in the mid well, encrustations cover the entire well casing. No slots visible (though could be below leachate level). In upper casing, some encrustations.
14	Rainham	482	1998	06/03/2002	Plastic	14.46	23.62	n/a	Some staining - especially around joints. No slots above leachate level, but no encrustation visible.
15	Rainham	610	1998	2002	7" Steel			0	Much steam in well clouding camera lens. Some staining on casing walls, though no obvious clogging of slots above leachate level. Can not see below.

	Site	Well No.	Well installed	Date of survey	Screen type	Leachate level (mBCT)	Base level (mBCT)	Estimated % of slot clogging	Observations
16	Rainham	716	1995	2002	Steel			0 - 40	Much encrustation around slots, though not below leachate level. Below leachate level, all slots open. Can see gravel pack through some slots.
17	Rainham	718	1995	01/05/2002	7" Steel	17.6	24.25	0 - 5	Foam in well, can not see casing easily. Much gas bubbling through leachate. In upper well, where can see slots, all fully open.
18	Rainham	726	1995	01/05/2002	7" Steel			0 - 25	Upper well shows some encrustation around slots. Much white and black surface staining. Can see pack through some slots. Within leachate all slots fully open, no clogging or staining.
19	Rainham	731	1995	01/05/2002	7" Steel			5 - 20	Much staining in upper well. Slots open, but some encrustations around slots. Can see pack trough some slots. Well blocked by waste in well.
20	Rainham	734	1995	01/05/2002	7" Steel	6.96	7.58	0 - 15	Much staining and rusting in upper casing. Some waste showing through slots. At leachate, slots open fully. Black and white staining around casing.
21	Rainham	776	1995	2002	Plastic			n/a	Well blocked at 15.30 m BCT. Some staining, though no clog deposits on pipe. Well failed above slotted casing.
22	Warnham	201	1994	22/03/2002	Steel	17.62	24.65	0 - 100	Much staining in upper well, though no encrustations. Slots open in casing above leachate level and can see some pack and some waste protruding into well. In the mid part of the well, above leachate level, slots 80-100 clogged, with much encrustation material around well screen.

	Site	Well No.	Well installed	Date of survey	Screen type	Leachate level (mBCT)	Base level (mBCT)	Estimated % of slot clogging	Observations
23	Warnham	204	1994	22/03/2002	Steel	15.03	19.2	50 - 100	Entire well screen encrusted in upper well. Some slots visible, though highly encrusted (80 %). In well just above leachate level 100% clogged slots.
24	Warnham	207	1994	22/03/2002	Plastic			50 - 100	Much staining and encrustations in upper well. Slots above leachate level 100 % clogged with white / grey deposits. Can not see slots below leachate level.
25	Warnham	217	1994	21/03/2002	Steel	19.81	22.3	0 - 100	Much staining and deposits in upper well. Entire sections of casing flaking off well screen. Slots visible, but highly encrusted. Mid well, casing fairly clean, but slots completely blocked by encrustations. Base of well visible - flakes of material (from above?). Within leachate, slots completely open, well screen clear of all deposits. Can see pack through some slots.
26	Warnham	218	1994	22/03/2002	Plastic	18.22	21.45	0 - 100	All slots fully open in upper well, though some staining on casing walls. In mid well, half the casing is clogged 100 %, this increases with depth to 100 % clogging around all the casing. Within leachate, casing stained black, but all slots are fully open.

PROJECT INFORMATION		DRILLING INFORMATION	
BOREHOLE NUMBER:	716	DRILLING TYPE:	Rotary barrel auger
TOTAL DEPTH:	14.55 m	WELL DIAMETER:	350 mm
SITE LOCATION:	Rainham Landfill	CASING DIAMETER:	178 mm OD
ELEVATION:	13.43 mOD	SCREEN TYPE:	Steel. 10 x 100 mm slots
DATE:	3/04/02	FILTER PACK:	20 mm gravel
		HIGH / LOW LEACH. LEVEL:	9.76 / 1.90 mOD
		LEACHATE LEVEL (AVE):	4.80 mOD

DEPTH mBCT / mOD	BOREHOLE CONSTRUCTION	INTERPRETED LITHOLOGY	OBSERVATIONS OF WASTE AND GRAVEL PACK	OBSERVATIONS OF CASING



OBSERVATIONS OF WASTE AND GRAVEL PACK

(2.0 m) Some silts in MSW. Bentonite around casing. Wet waste (mostly plastic bags, paper and wood).

(2.6 m) Layer of soil with much rubble. Borehole annulous fully open.

(3.2 m) MSW. Moist. Mostly glass bottles, wood, plastic and paper.

(5.5 m) Layer of soils and rubble within MSW. Wet.

(5.7 m) MSW. Top of gravel pack.

(8.1 m) MSW. Gravel pack loose and uncemented, but covered in wet orange-black slime. The slime does not bind the gravel.

(8.6 m) Gravel very dirty.

(8.7 m) Horizon of silty clay.

(9.0 m) MSW.

(9.2 m) Horizon silty clay. Gravel contaminated with cover soils.

(9.6 m) MSW. Gravel pack clean and free running when exposed.

(11.6 m) Gravel has some orange staining.

(12.8 m) MSW. Gravel pack free running and appears clean.

(13.1 m) Hydraulic fill, no MSW. Gravel pack fully contaminated with black silts.

OBSERVATIONS OF CASING

(0.0 - 1.33 m) Plain casing. Much surface corroison internally and externally. Pitting and flaking of steel.

(1.33 - 3.70 m) Plain casing with much corrosion and flaking. nodules and pitting on out casing.

(3.70 - 7.15 m) Slotted screen. Slots mostly closed with encrustations. Less flaking and corrosion with depth.

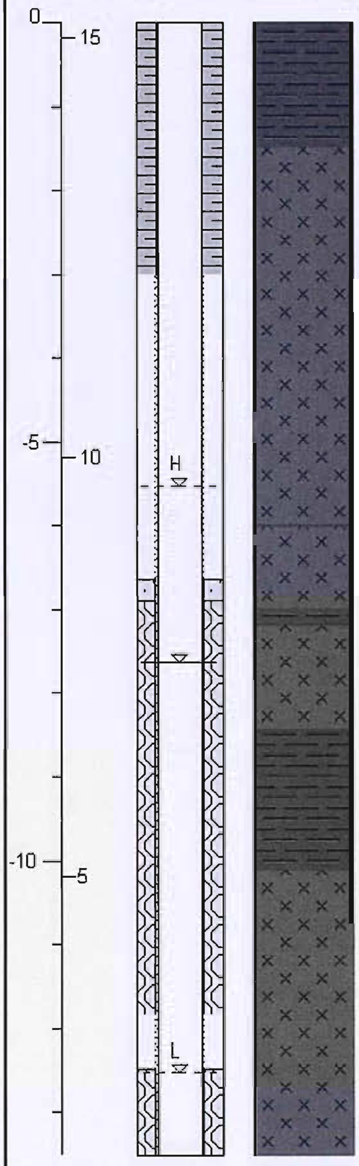
(7.15 - 10.15 m) Slotted screen. Much corrosion at top of section with flaking of steel and most slots fully closed. Towards bottom of section there is less corrosion and less flaking and all slots are open.

(10.15 - 12.31 m) Slotted screen with base plate. Some flaking and precipitation on outer surface of screen. Slots all fully open to the base of the section. Lowest 2m of casing completely filled with silty, sandy deposits.

Well log and observations from the exhumation of well 716, Rainham landfill

PROJECT INFORMATION		DRILLING INFORMATION	
BOREHOLE NUMBER:	730	DRILLING TYPE:	Rotary barrel auger
TOTAL DEPTH:	13.52 m	WELL DIAMETER:	350 mm
SITE LOCATION:	Rainham Landfill	CASING DIAMETER:	178 mm OD
ELEVATION:	15.18 mOD	SCREEN TYPE:	Steel. 10 x 100 mm slots
DATE:	3/04/02	FILTER PACK:	20 mm gravel
		HIGH / LOW LEACH. LEVEL:	8.63 / 0.97 mOD
		LEACHATE LEVEL (AVE):	5.87 mOD

DEPTH mBCT / mOD	BOREHOLE CONSTRUCTION	INTERPRETED LITHOLOGY	OBSERVATIONS OF WASTE AND GRAVEL PACK	OBSERVATIONS OF CASING



OBSERVATIONS OF WASTE AND GRAVEL PACK

(1.5 m) Cover soil and MSW. Some brick and concrete rubble and firm grey clay.

(6.0 m) MSW. Waste compacted and smeared around borehole walls. Newspaper dated 1987.

(6.2 m) Firm pebbly blue clay.

(6.8 m) Sand buffer above gravel pack.

(6.9 m) Start of gravel pack. Gravel contaminated with sand and cover soils from waste. Some waste pieces in gravel from the sides of the well.

(7.0 m) Firm clay with much rubble, brick pebbles and concrete.

(7.2 m) MSW.

(8.0 m) MSW

(8.4 m) Cover soils. Gravel pack clean and free running.

(10.1 m) MSW. Gravel pack clean and free running.

(10.6 m) MSW, wet.

(11.8 m) Possible bridge in the gravel pack.

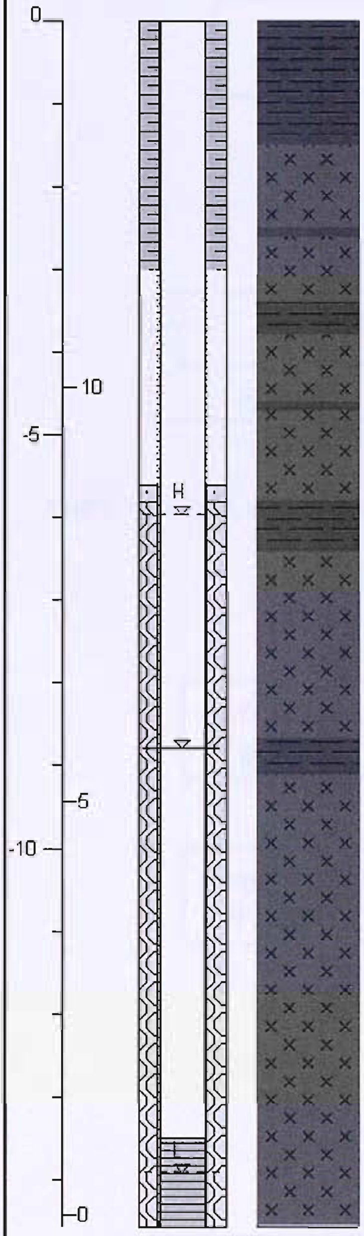
OBSERVATIONS OF CASING

It was not possible to remove the well screen from the excavation.

Well log and observations from the exhumation of well 730, Rainham landfill

PROJECT INFORMATION		DRILLING INFORMATION	
BOREHOLE NUMBER:	734	DRILLING TYPE:	Rotary barrel auger
TOTAL DEPTH:	14.58 m	WELL DIAMETER:	350 mm
SITE LOCATION:	Rainham Landfill	CASING DIAMETER:	178 mm OD
ELEVATION:	14.43 mOD	SCREEN TYPE:	Steel. 10 x 100 mm slots
DATE:	3/04/02	FILTER PACK:	20 mm gravel
		HIGH / LOW LEACH. LEVEL:	8.63 / 0.67 mOD
		LEACHATE LEVEL (AVE):	5.80 mOD

DEPTH mBCT / mOD | BOREHOLE CONSTRUCTION | INTERPRETED LITHOLOGY | OBSERVATIONS OF WASTE AND GRAVEL PACK | OBSERVATIONS OF CASING



OBSERVATIONS OF WASTE AND GRAVEL PACK

(2.0 m) Cover soils becoming black. Below soil is a horizon of rubble with large (> 1m) concrete blocks. Below rubble is MSW.

(2.5 m) MSW. Mostly plastic bags and cardboard. Wet and dripping when exposed. MSW interspaced with horizons of clay.

(3.4 m) MSW. Dry. newspaper dated from 1987.

(3.8 m) Horizon of cover soils. Well bore fully open.

(4.6 m) MSW. Well bore fully open.

(4.7 m) Horison of silt and clay.

(5.8 m) MSW. Top of gravel pack.

(6.4 m) Cover soils interspaced with MSW. MSW moist to damp containing mostly rags, paper and wood.

(8.7 m) MSW

(9.1 m) Black silty clays. Gravel pack contaminated with soil.

(9.5 m) MSW. Gravel pack clean and uncemented.

(9.6 m) Gravel pack clean and free running.

(10.8 m) Gravel pack clean and free running.

(to base) No further observation could be made due to the depth of the excavation. However, clean gravel could be seen at the base of the well.

OBSERVATIONS OF CASING

(0 - 2.85 m) Plain casing showing corrosion and flaking of steel both internally and externally. Extent of corrosion increases with depth of section.

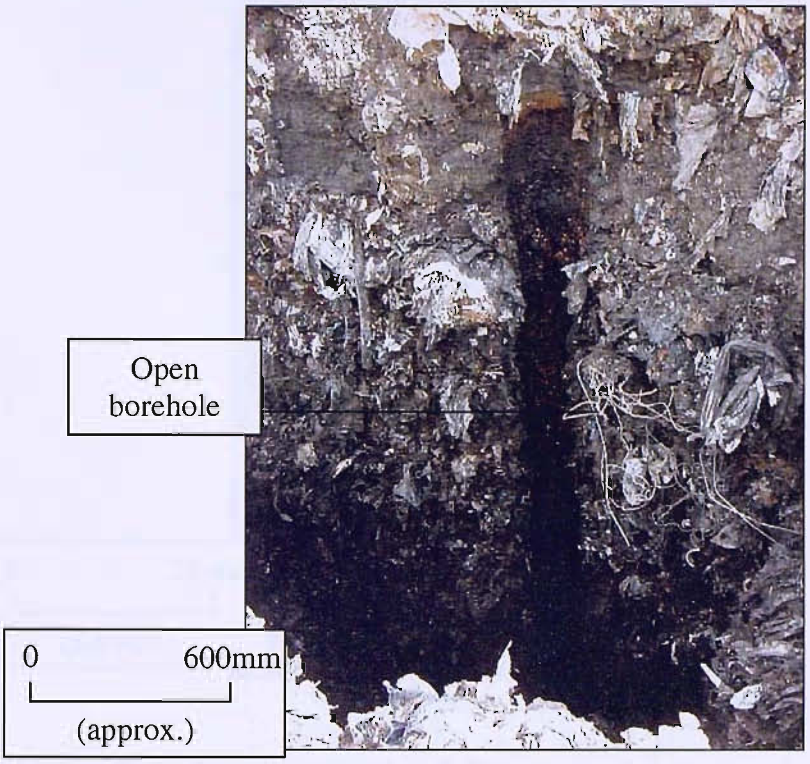
(2.85 - 5.78 m) Slotted screen. External casing extremely corrosed. Large flakes of steel fall from casing. Most slots blocked by precipitates.

(5.78 - 8.72 m) Slotted screen. Very little corrosion both internally and externally. Some surface rusting, but no flaking. All slots are fully open.

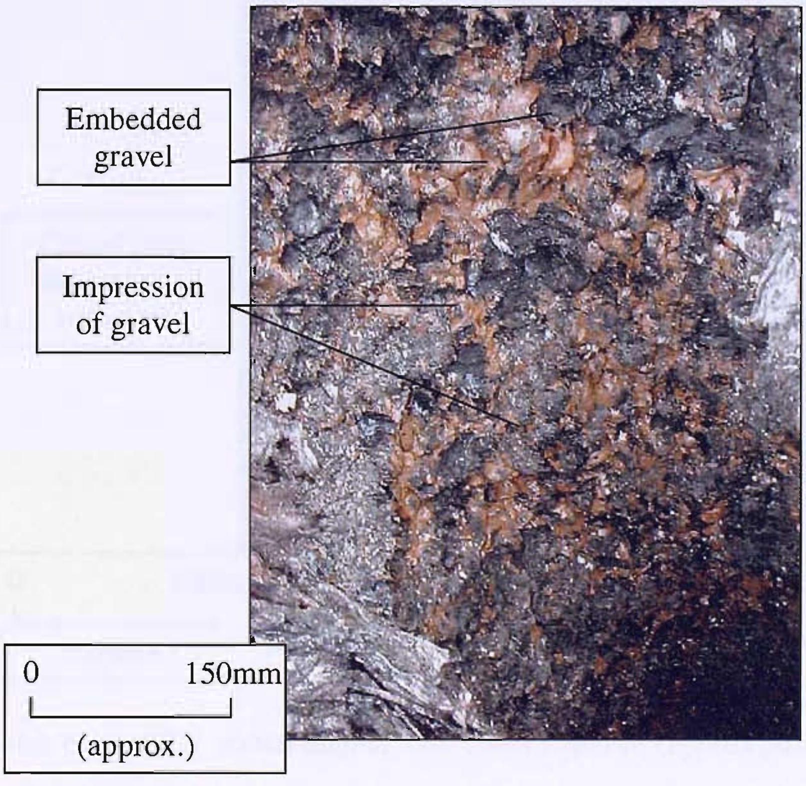
(8.72 - 11.60 m) Slotted screen. Very little corrosion both internally and externally. Some surface rusting. All slots are open.

(11.60 - 14.57 m) Slotted screen. Some surface rusting but no flaking. Lower slots clogged with waste and soils.

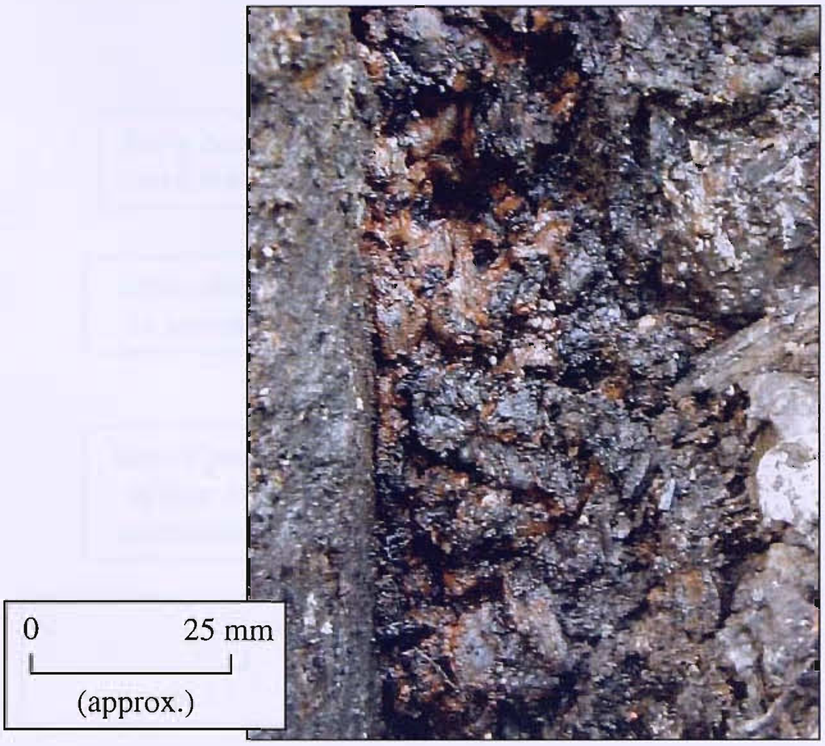
Well log and observations from the exhumation of well 734, Rainham landfill



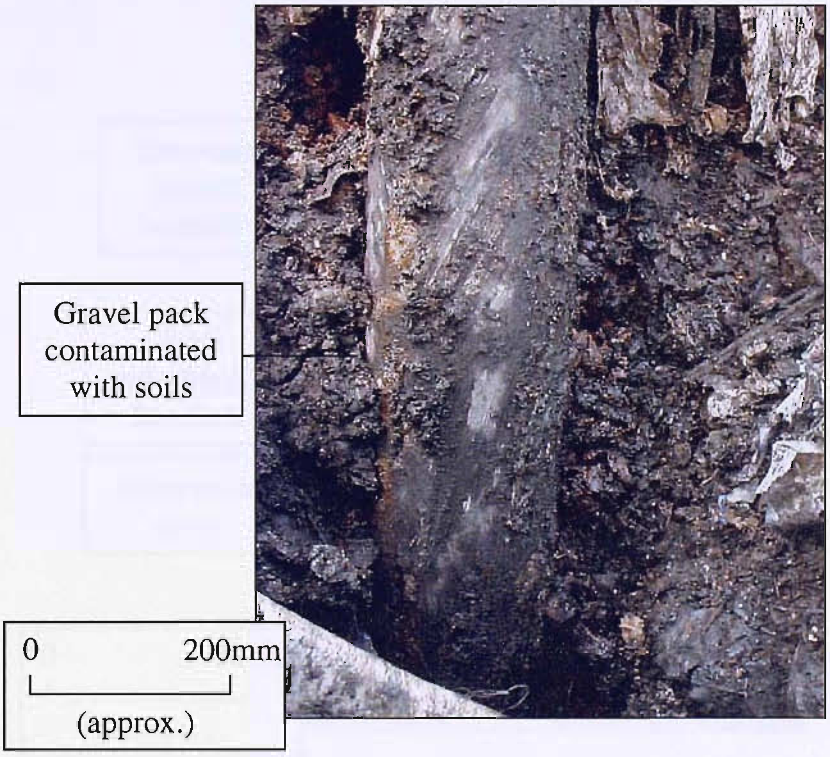
Open borehole to the base of the excavation (approximately 0.5 to 5 mOD), exposed during the exhumation of well 716



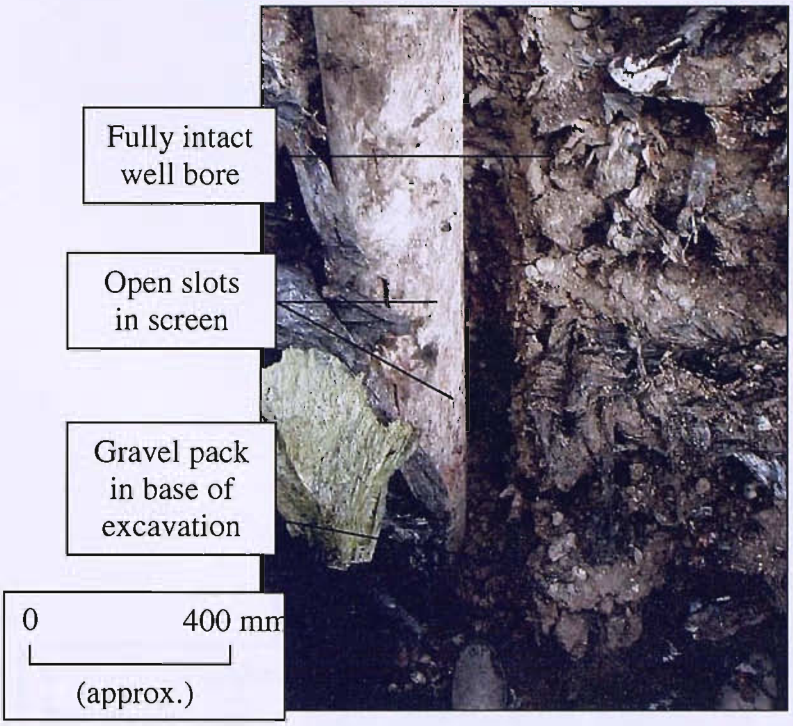
Embedded gravel and impressions of gravel in borehole walls, exposed during the exhumation of well 716



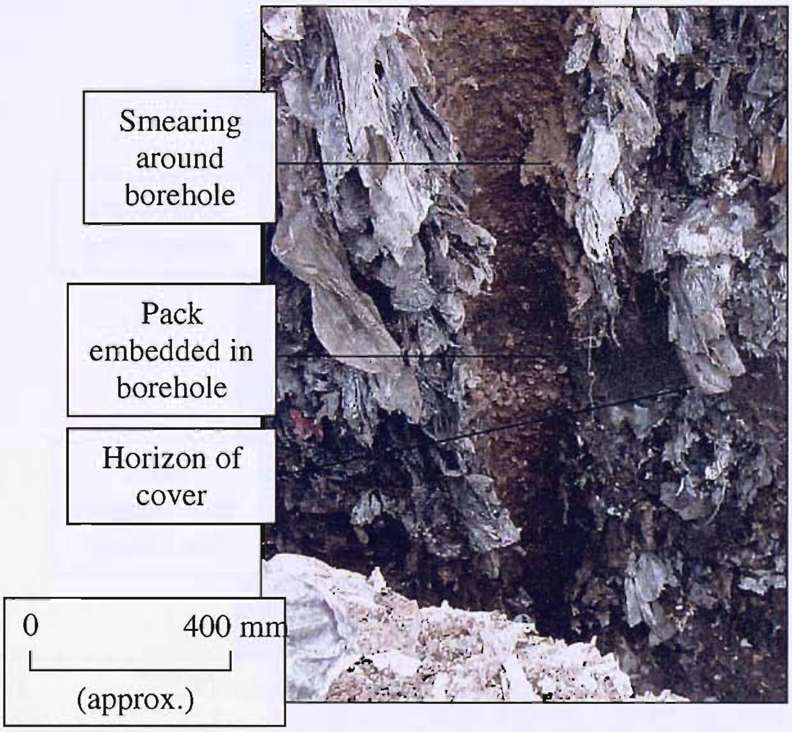
Microbial fouling of gravel pack of well 716 observed during well exhumation (approximately 5.3 mOD)



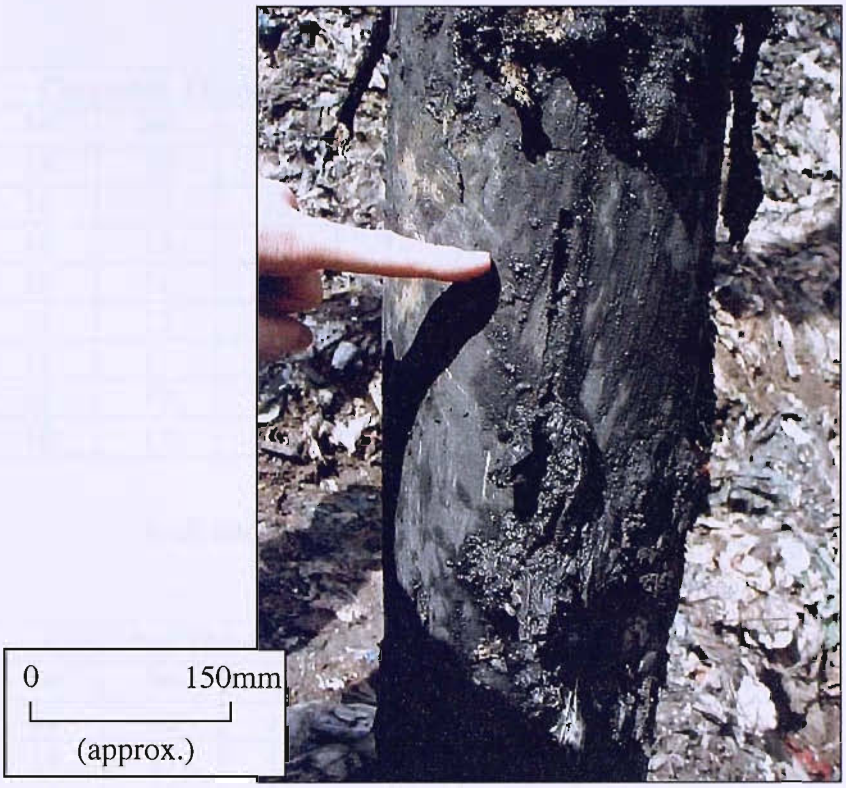
Gravel pack of well 716 contaminated with cover material (approximately 4.8 mOD)



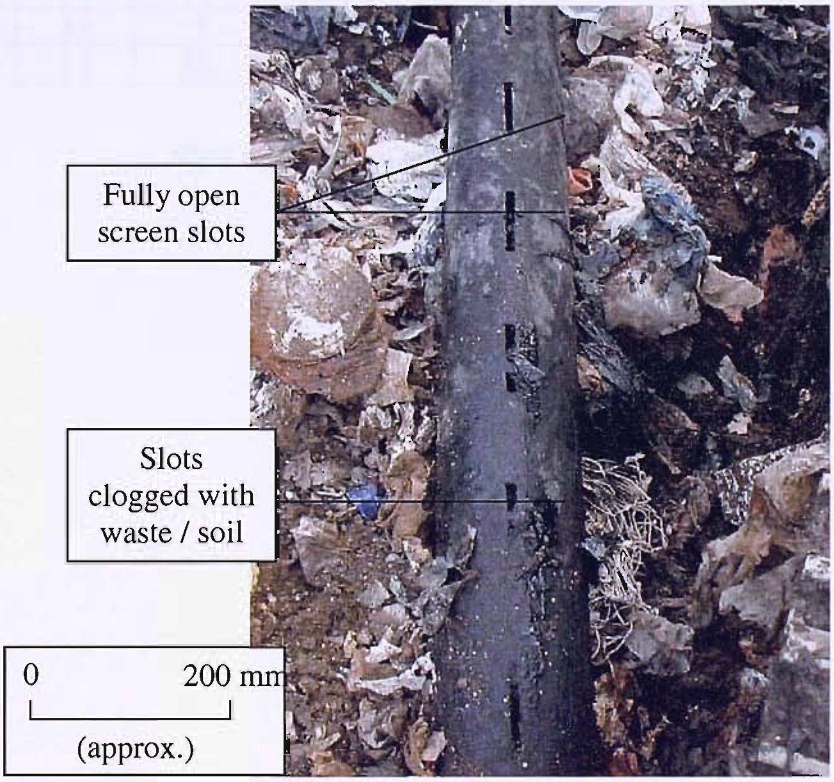
Open well bore during the exhumation of well 734. Well screen slots are visible and the gravel pack can be seen at the base of the exposed section



Open well bore showing possible smearing and gravel embedded in a horizon of cover soils (5.3 mOD), observed during the exhumation of well 734



Well screen slots of well 716 clogged with waste and soil (approximately 1.5 mOD)



Clean well screen slots of well 734 clogged from within the saturated zone (approx. 2 to 0 mOD)

mBCT	Corroded Thickness (mm)				Cleaned Thickness (mm)			
	1st	2nd	3rd	Ave	1st	2nd	3rd	Ave
1.10	15	12	13	13.3	11	10	7	9.3
1.80	16	12	15	14.3	7	11	11	9.6
2.60	16	13	13	14	9	10	10	9.6
3.40	12	11	11	11.3	11	10	10	10.3
4.16	14	15	14	14.3	10	9	10	9.6
4.96	11	11	15	12.3	8	10	10	9.3
5.73	11	12	11	11.3	10	11	11	10.6
6.51	10	11	11	10.6	10	10	10	10

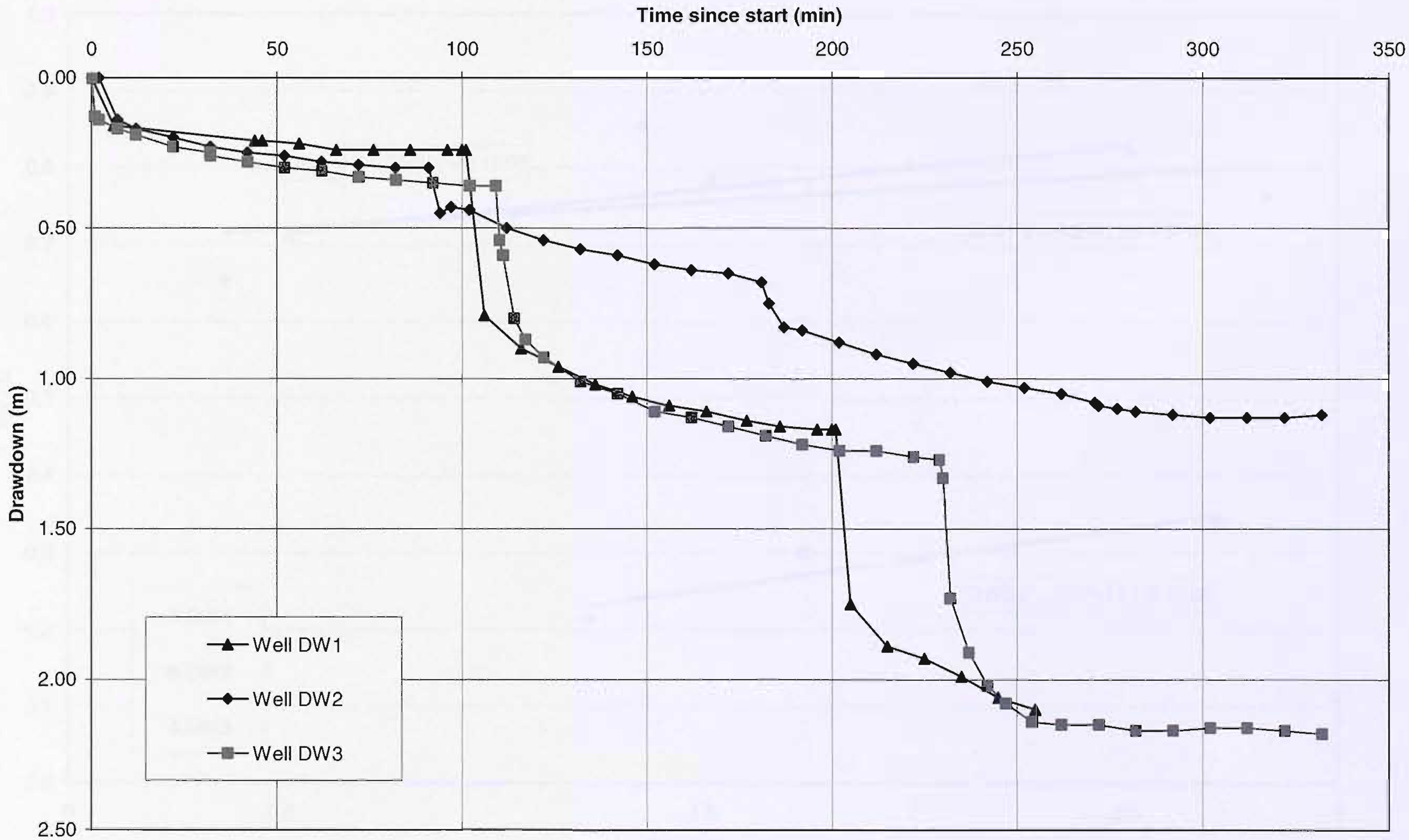
Wall thickness of casing from well 716

mBCT	Corroded Thickness (mm)				Cleaned Thickness (mm)			
	1st	2nd	3rd	Ave	1st	2nd	3rd	Ave
0.12m	11	12	11	11	9	9	9	9
1.91m	14	15	15	15	8	9	9	9
3.07m	14	15	14	14	10	10	10	10
5.07m	12	12	12	12	12	11	11	11
5.90m	14	15	14	14	12	12	11	12
8.00m	11	11	12	11	10	9	10	10
10.12m	11	13	11	12	11	11	11	11
12.07m	11	11	13	12	11	10	11	11
14.00m	11	12	11	11	10	11	11	11

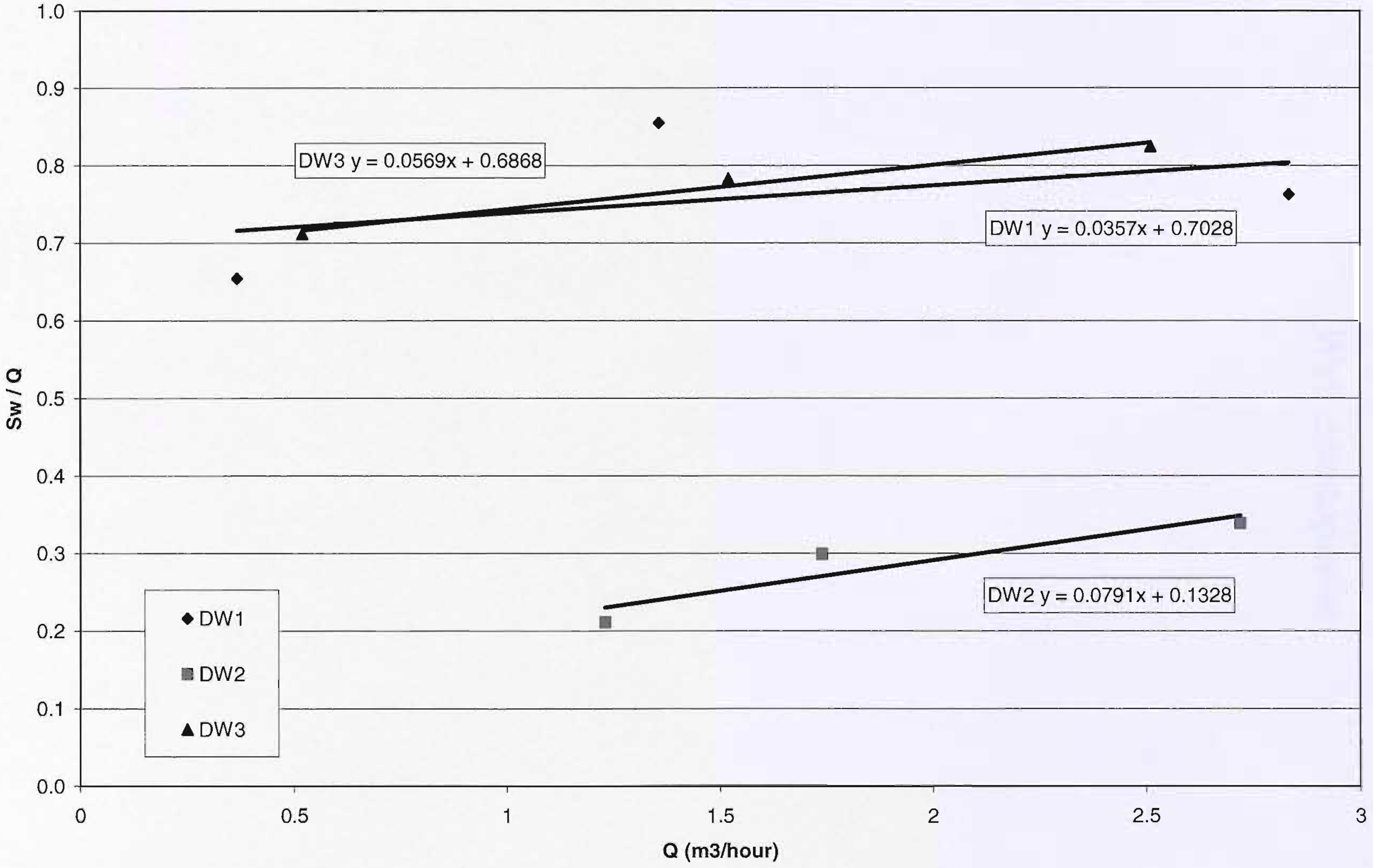
Wall thickness of casing from well 734

Appendix C

Drilling trials



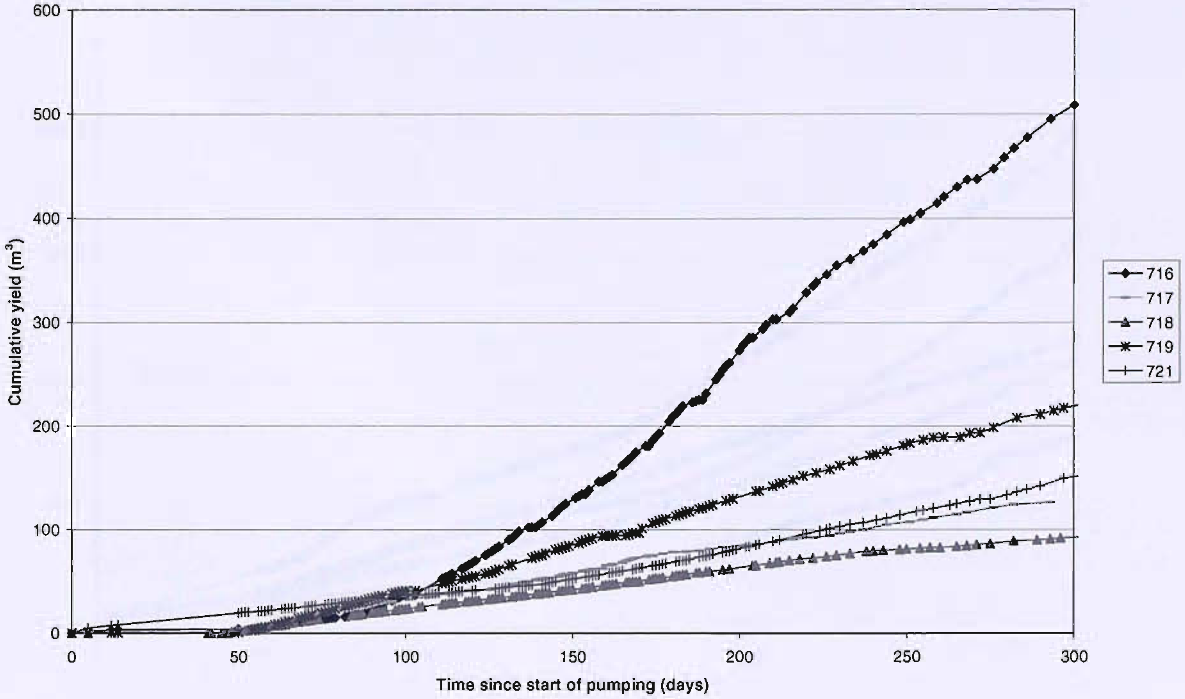
Step test drawdown data



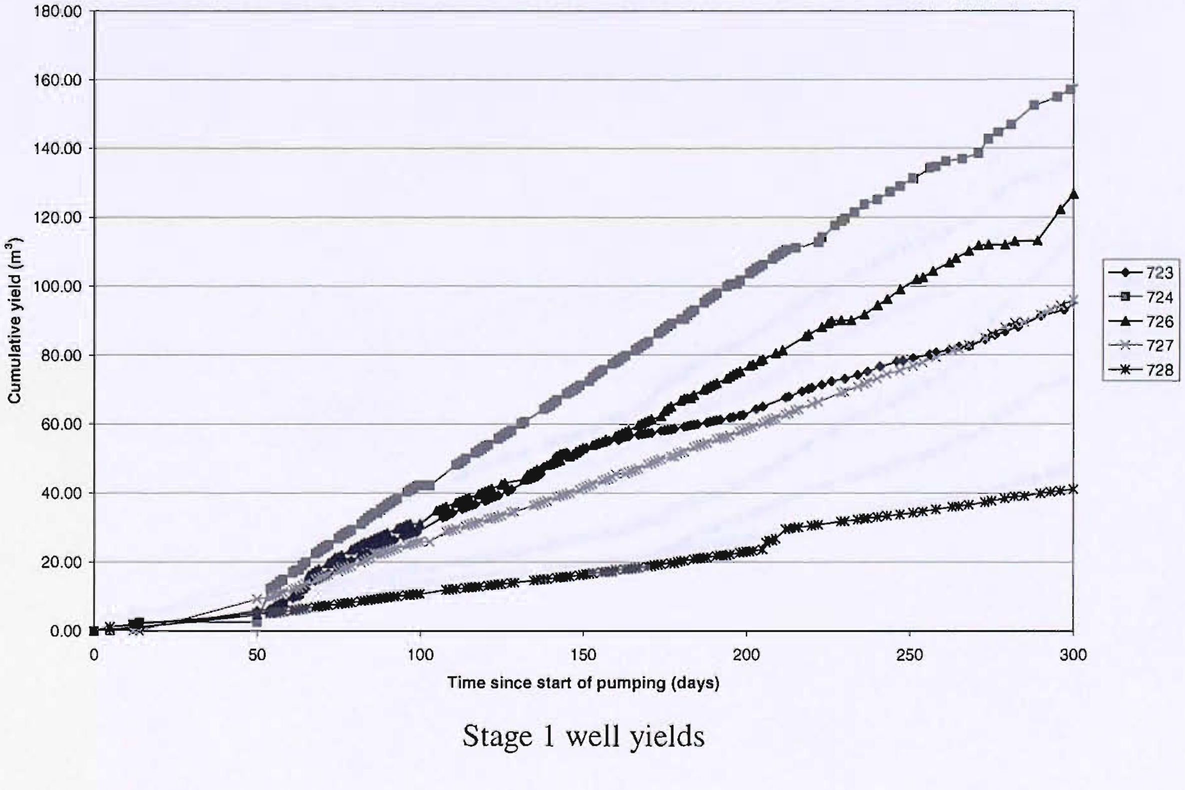
Step test analysis (Hantush and Bierschenk, 1963)

Appendix D

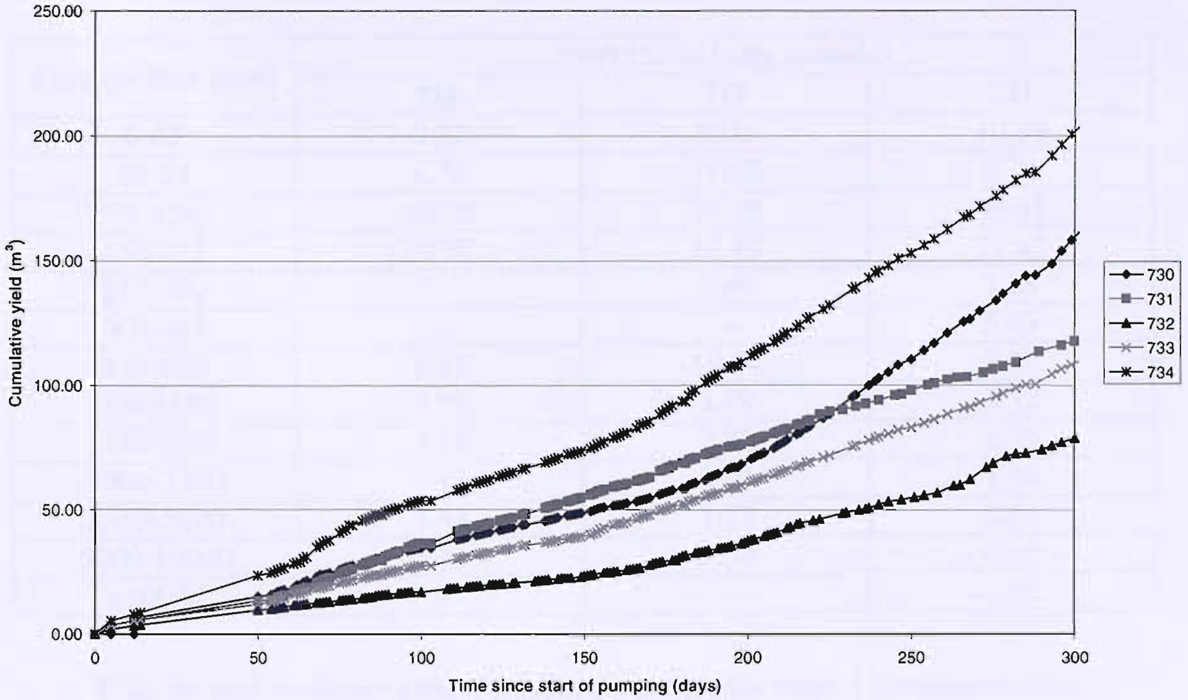
Well development



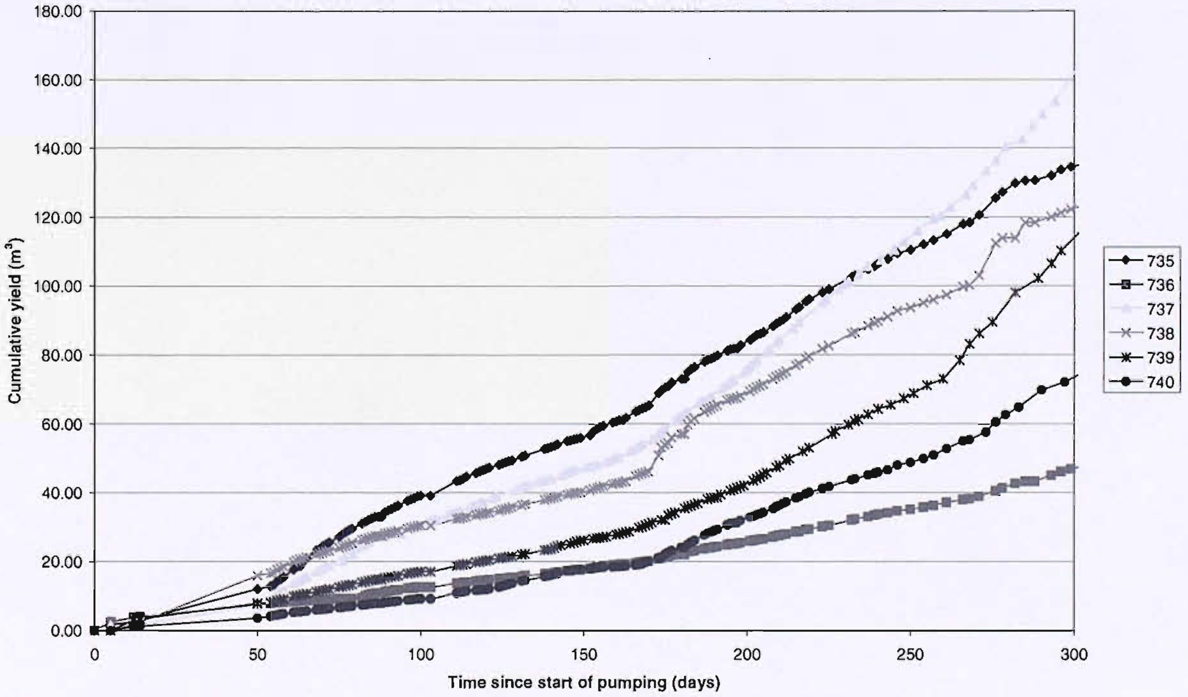
Stage 1 well yields



Stage 1 well yields



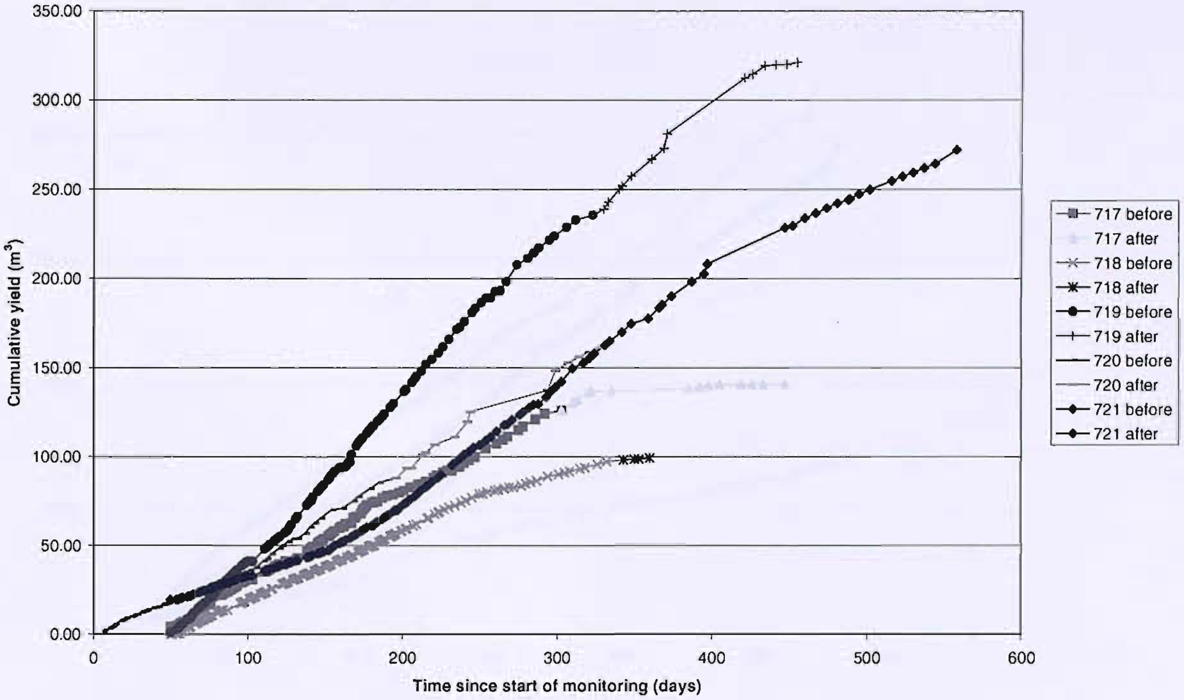
Stage 1 well yeilds



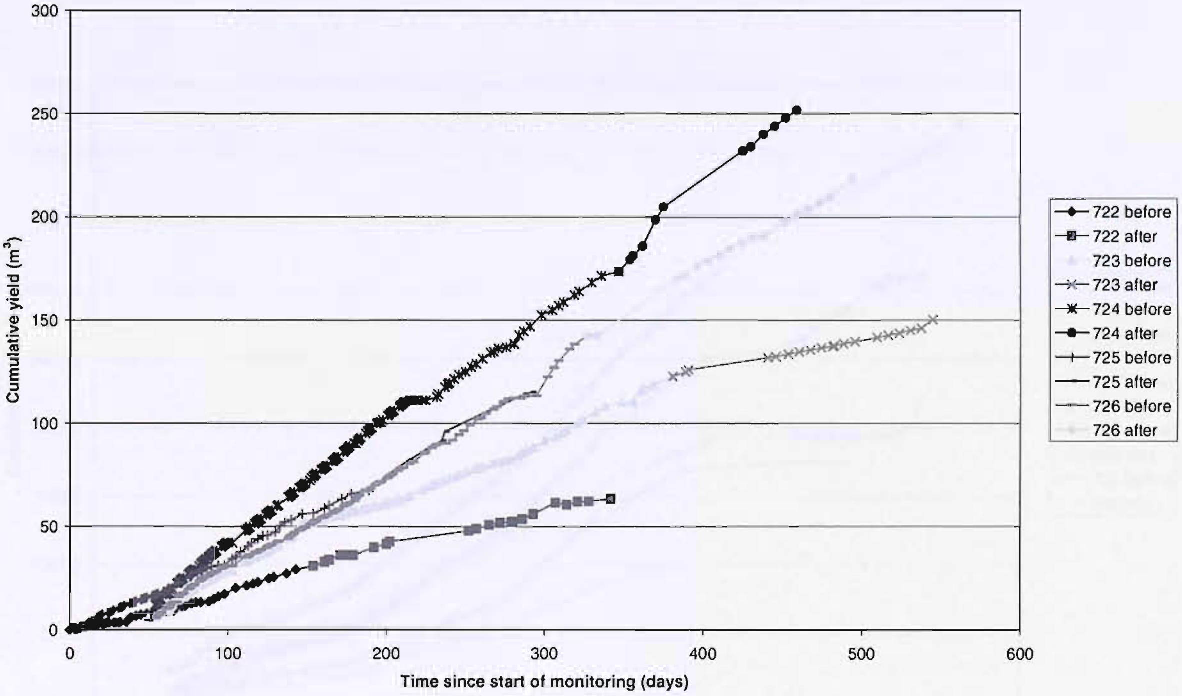
Stage 1 well yeilds

Particle Size (μm)	**PSD (% of bulk sample)**		
	716	**717**	**731**
0-63	0.32	9.00	10.08
63-75	4.72	11.67	2.75
75-150	48.09	35.29	40.85
150-212	25.07	13.86	21.07
212-300	-	7.69	7.88
300-425	-	-	5.83
425-600	8.65	10.94	3.11
600-1180	4.09	3.49	4.32
1180-2000	2.19	2.81	1.79
2000-3350	2.13	2.69	1.34
3350-5000	1.44	1.22	0.51
5000-10000	3.31	1.34	0.45
>10000	-	-	0.02

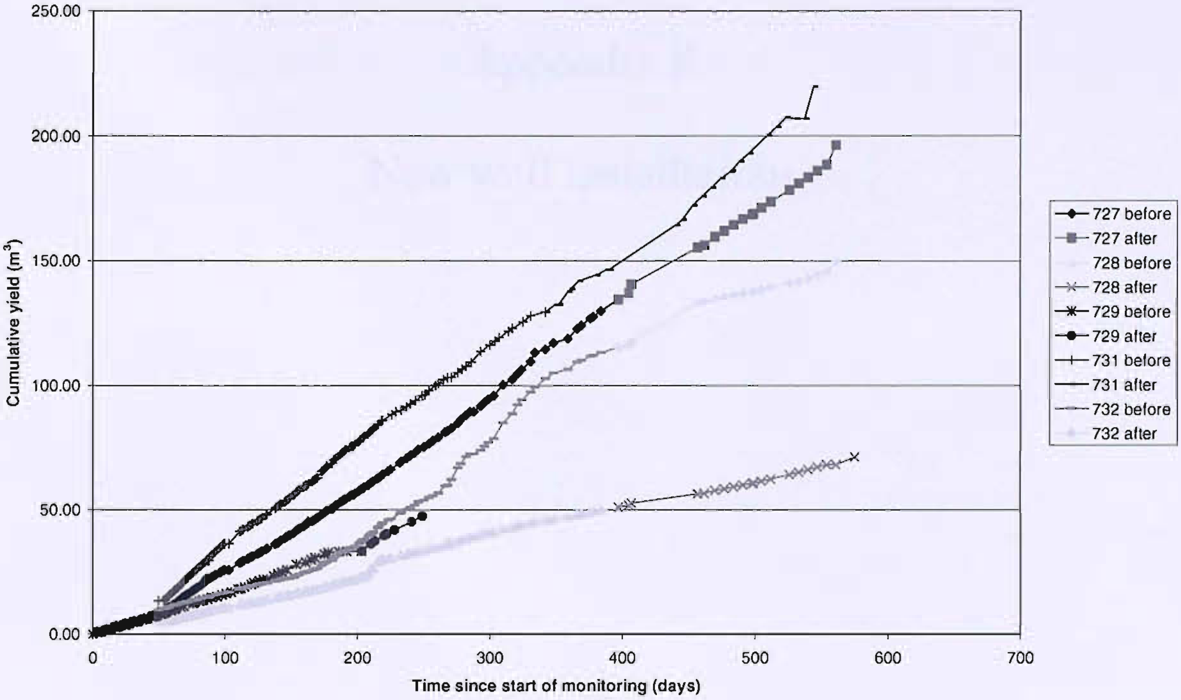
PSD for bulk sediment samples collected during the stage 1 developent trial



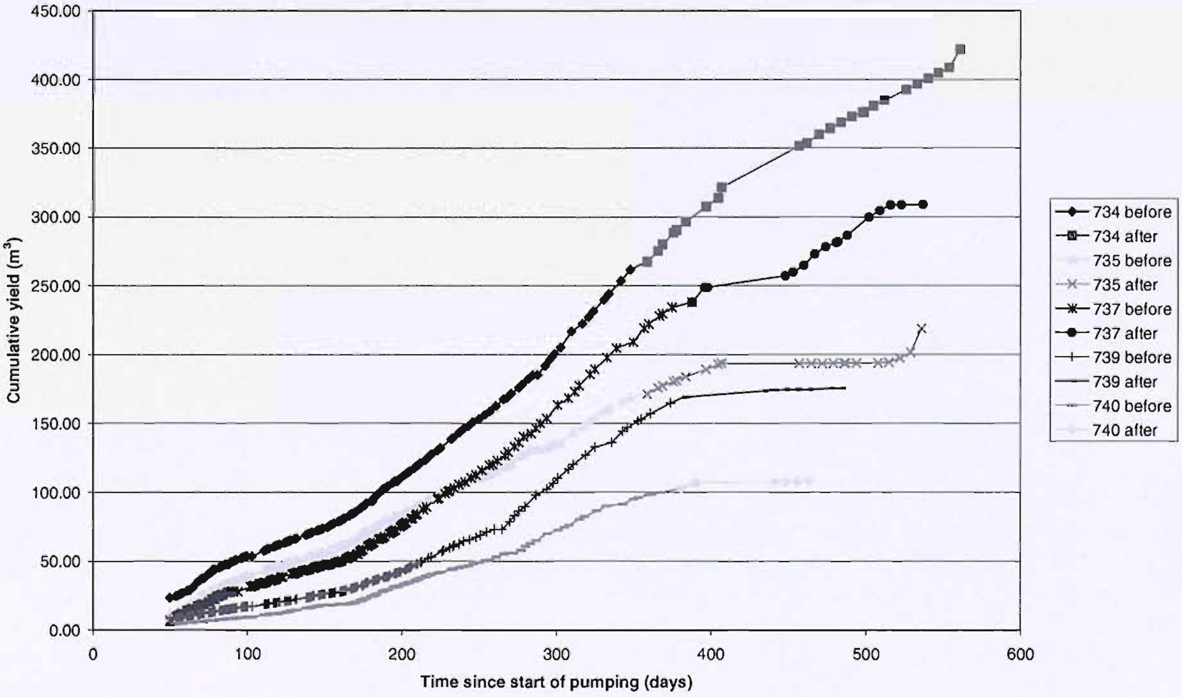
Stage 2 well yeilds



Stage 2 well yeilds



Stage 2 well yeilds



Stage 2 well yeilds

Appendix E

New well installations

Item	Westbury	Typical MSW leachate	
	Range	Acetic	Methanogenic
pH	8.95 - 10.06	4.5-7.5	7.5-9.0
Conductivity	3090.9 - 43000	5000-30000	2500-15000
COD	902.2 - 12020	6000-60000	500-4500
BOD		4000-40000	20-550
TOC	463.3 - 3101.5	1000-20000	100-750
TS		8000-50000	1000-3000
SS	622.3 - 770.4	200-2500	100-500
Alkalinity	3763.8 - 9136	300-11500	
NH-N	199.3 - 694.6	30-3000	
VFA	94.9 - 4258-3		
Cl	4862.8 - 9571.8	500-5000	100-500
SO_4	288.7 - 8240.8	70-1750	10-420
PO_4	5.8 - 36.5	5-100	<10
NO_4	0.2 - 0.6	0.1-75	
K	7694.6 - 11660	10-2500	
Na	1331.8 - 3020.3	5-4000	
Ca	99.6 - 173.7	10-2500	20-600
Mg	51.9 - 821.7	50-1150	40-350
Fe	124.5 - 553.7	20-2100	3-280
Mn	3.9 - 16.0	0.3-65	0.03-45
Ni	1.4 - 2.1	0.02-2.05	
Cu	0.4 - 0.5	0.01-1.4	

Comparison of leachate chemistry from Westbury and a typical MSW leachate
(All units in mg/l except pH and conductivity: µs/cm)

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BOREHOLE KEY

INSTALLATION MATERIAL / LITHOLOGY	LITHOLOGICAL DESCRIPTION
▤	BENTONITE SEAL
■	BACKFILL
░	FILTER SAND / GRAVEL
▨	PREBONDED FILTER PACK
■	TOPSOIL
■	CLAY COVER MATERIAL
▩	**CKD / MSW**
☒	MSW (MUNICIPLE SOLID WASTE)
▨	MSW / CKD
□	NO RETURNS
■	BASE CLAY

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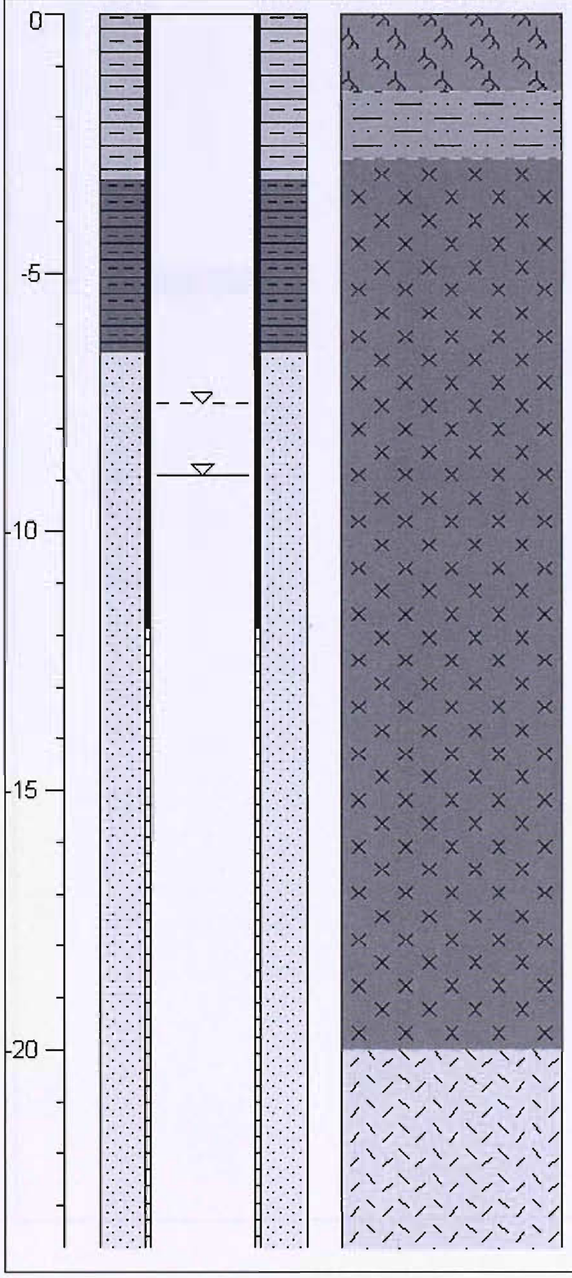
FIELD BOREHOLE LOG

BOREHOLE NUMBER:	31A
TOTAL DEPTH:	35.30m
PAGE:	1 of 2

PROJECT INFORMATION	
PROJECT:	Westbury Drilling Trial
SITE LOCATION:	Westbury Landfill
EASTING / NORTHING:	388157.24 / 152652.11
ELEVATION:	64.86mOD
DRILLED BY:	WME Drilling
LOGGED BY:	Tristan Rees-White
DATE STARTED	4th September 2003
DATE COMPLETED:	5th September 2003

DRILLING INFORMATION		
DRILLING TYPE:	Rotary	
WELL DIAMETER:	300mm	
CASING DIAMETER:	168mm OD / 150mm ID	
SCREEN TYPE:	Stainless steel wire-wrap	
SLOT SIZE:	0.5mm	
FILTER PACK:	0.5-0.8mm filter sand	
WATER STRUCK (BGL):	7.50m	- ▽ -
FINAL WATER LEVEL:	8.91m	▽

DEPTH | BOREHOLE CONSTRUCTION | INTERPRETED LITHOLOGY | LITHOLOGICAL DESCRIPTION



TOPSOIL

CLAY COVER

MSW

Dry, some concrete blocks.

Leachate struck.

Some leachate in waste, though not saturated, overlying a band of dry CKD.
Bands of gravely black soil.

CKD. Damp grey/ black. Waste wet above CKD.

MSW. Dry but leachate entering well from above. Paper, plastics and metal with black/grey soil matrix.

Firm to hard, blue/grey, wet, gravely CKD.

Slow drilling.

MSW. Dry, with partialy decomposed shredded paper, wood, plastics and much CKD.

Much plastic.

CKD

Very hard horizon. Much leachate/slurry entering well from above.

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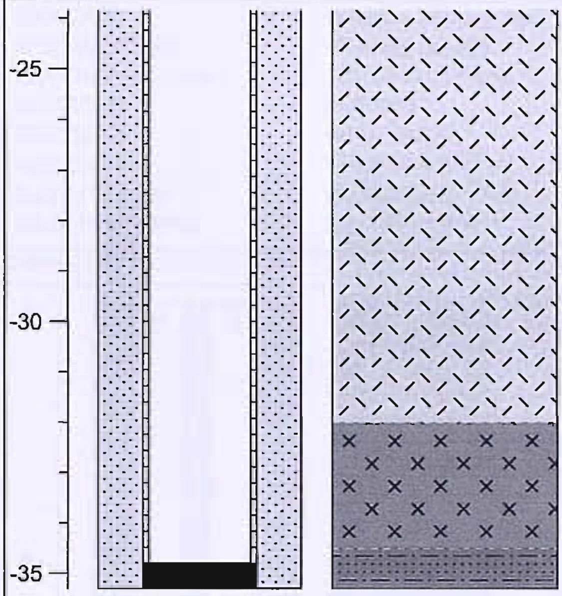
FIELD BOREHOLE LOG
BOREHOLE NUMBER: 31A
TOTAL DEPTH: 35.30m
PAGE: 2 of 2

DEPTH	BOREHOLE CONSTRUCTION	INTERPRETED LITHOLOGY	LITHOLOGICAL DESCRIPTION



Very hard CKD, overlain by slurry entering well from above.

Hard, dry CKD.

Hard, dry CKD.

Hard, dry CKD.

Soft, uncemented, friable damp CKD.

MSW. Shredded decomposed with some soil horizons.

Plastics, black gravely soil and some fabrics.

CLAY. Dark grey/blue, v shelly, v firm virgin clay.

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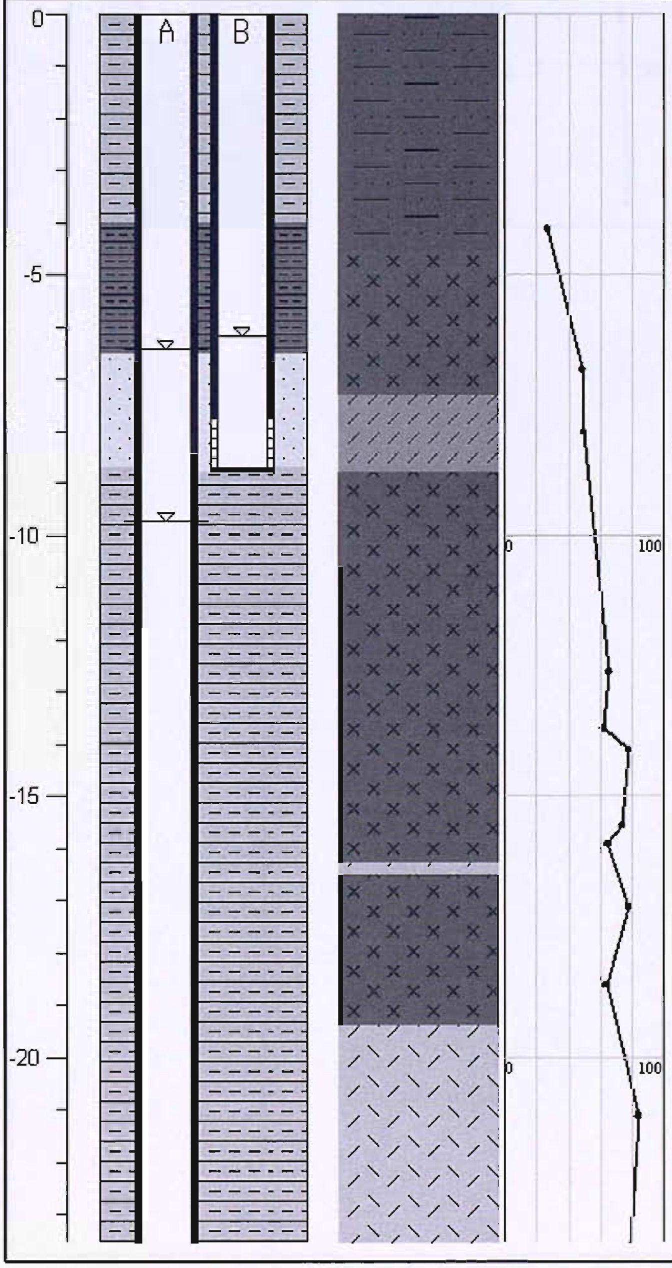
FIELD BOREHOLE LOG

BOREHOLE NUMBER:	31P1
TOTAL DEPTH:	33.10m
PAGE:	1 of 2

PROJECT INFORMATION		DRILLING INFORMATION	
PROJECT:	Westbury Drilling Trial	DRILLING TYPE:	Rotary
SITE LOCATION:	Westbury Landfill	WELL DIAMETER:	300mm
EASTING / NORTHING:	388152.45 / 152656.20	CASING DIAMETER:	90mm OD / 83mm ID
ELEVATION:	65.43 mOD	SCREEN TYPE:	PVC cut slot
DRILLED BY:	WME Drilling	SLOT SIZE:	1.0mm
LOGGED BY:	Tristan Rees-White	FILTER PACK:	5mm gravel
DATE STARTED	10th September 2003	WATER STRUCK (BGL):	9.70m ▽
DATE COMPLETED:	11th August 2004	FINAL WATER LEVEL:	A. 6.40m / B. 6.16m ▽

DEPTH	BOREHOLE CONSTRUCTION	INTERPRETED LITHOLOGY / TEMPERATURE	LITHOLOGICAL DESCRIPTION



CLAY COVER

27°C

MSW

Dry, undecomposed plastics and fabrics.
MSW. 49 °C. Much black matrix.

Moist MSW / CKD mix. Layered within waste. 50 °C

Saturated band. Damp MSW below.
MSW. Mostly plastics, fabric, some wood, in black clayey matrix.
Wet from 11-11.5m.
Dry, grey/black gravely soil. Wet above, dry beneath.

MSW. 66 °C, dry.

62 °C, dry though leachate above.
78°C, Much water above.

74°C
65°C
CKD. Dry, friable.

MSW. 78°C, damp, fairly decomposed, though some readable paper.

64°C. Very wet above.

84°C. Band of v hard CKD beneath.

CKD

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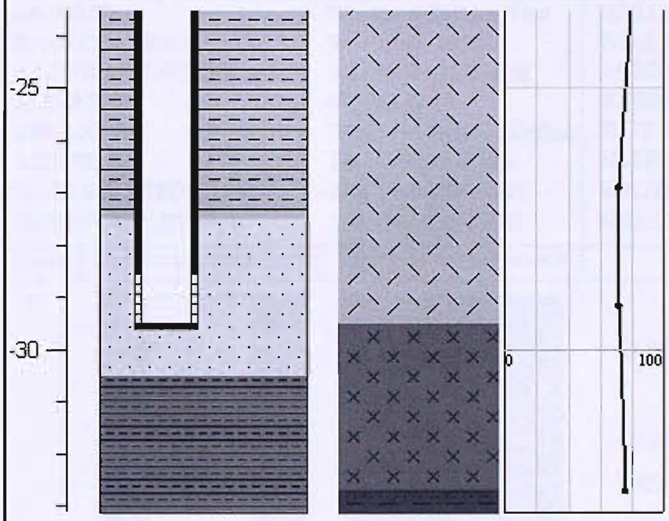
FIELD BOREHOLE LOG

BOREHOLE NUMBER:	31P1
TOTAL DEPTH:	33.10m
PAGE:	2 of 2

DEPTH | BOREHOLE CONSTRUCTION | INTERPRETED LITHOLOGY / TEMPERATURE | LITHOLOGICAL DESCRIPTION



72°C. Hard CKD.

72°C. Hard CKD.

MSW

CLAY. 76°C. Blue/grey, v shelly virgin clay.

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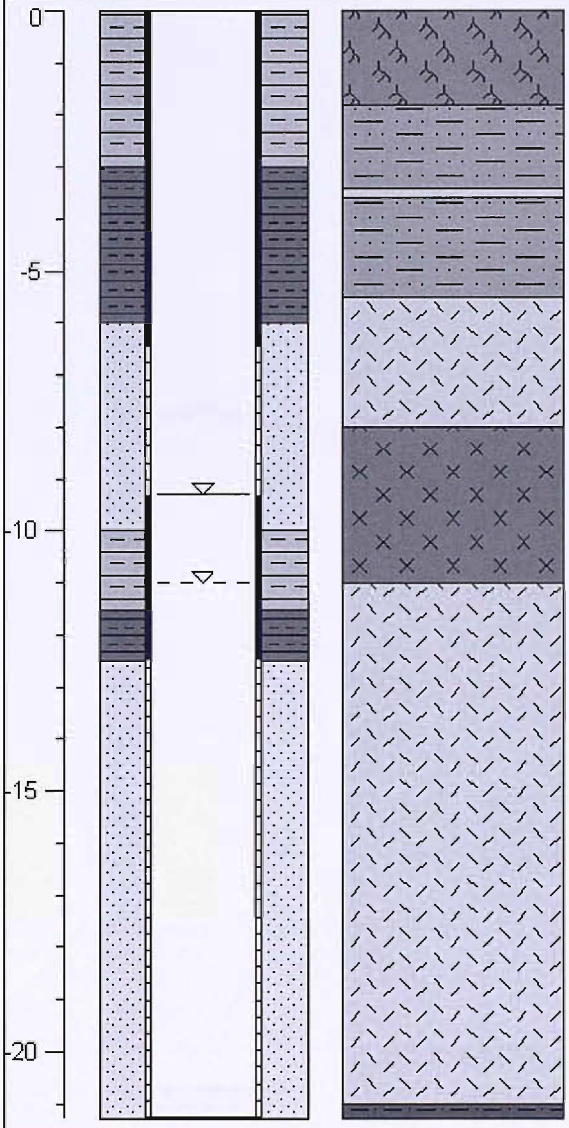
FIELD BOREHOLE LOG

BOREHOLE NUMBER:	36A
TOTAL DEPTH:	21.30m
PAGE:	1 of 1

PROJECT INFORMATION		DRILLING INFORMATION	
PROJECT:	Westbury Drilling Trial	DRILLING TYPE:	Rotary / Shell & Auger
SITE LOCATION:	Westbury Landfill	WELL DIAMETER:	300mm
EASTING / NORTHING:	388177.47 / 152928.46	CASING DIAMETER:	168mm OD / 150mm ID
ELEVATION:	65.36mOD	SCREEN TYPE:	Stainless steel wire-wrap
DRILLED BY:	WME / Well Head Drilling	SLOT SIZE:	0.5mm
LOGGED BY:	Tristan Rees-White	FILTER PACK:	0.5 - 0.8mm filter sand
DATE STARTED	25th September 2003	WATER STRUCK (BGL):	11.00m - ▽ -
DATE COMPLETED:	10th November 2003	FINAL WATER LEVEL:	8.88m ▽

DEPTH	BOREHOLE CONSTRUCTION	INTERPRETED LITHOLOGY	LITHOLOGICAL DESCRIPTION



TOPSOIL

CLAY COVER

CKD. Some gravel.

CLAY. Much gravel, brick and stone present.

CKD. Dry, grey and friable.

MSW. Dry and undecomposed paper, plastic, wood and glass.

MSW. Becoming wet.

CKD. Dry.

Dry.

Dry.

CKD. Very wet.

CLAY

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FIELD BOREHOLE LOG

BOREHOLE NUMBER:	36B
TOTAL DEPTH:	21.05m
PAGE:	1 of 1

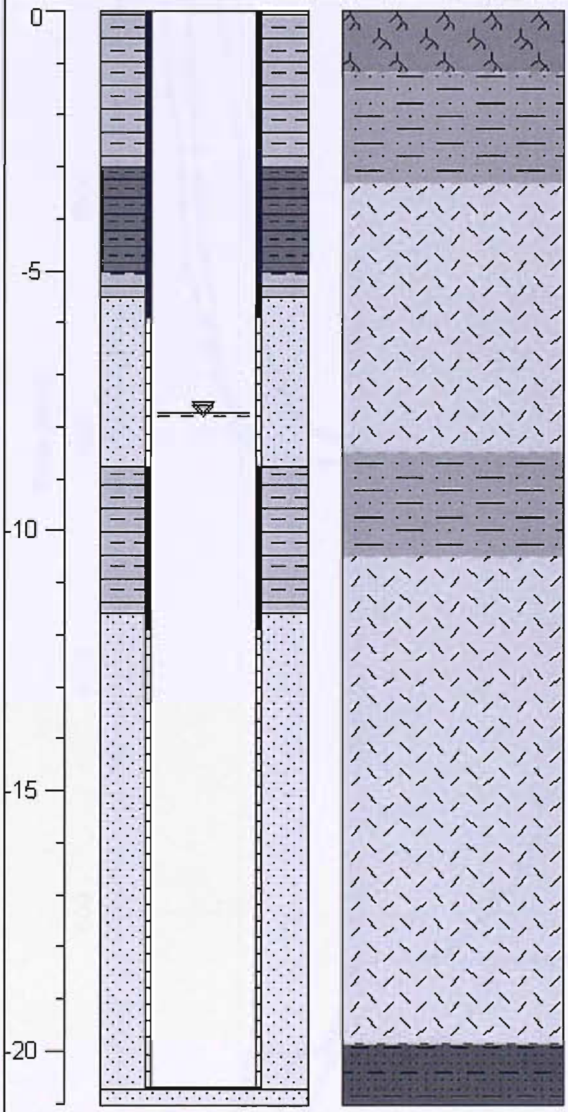
PROJECT INFORMATION

PROJECT:	Westbury Drilling Trials
SITE LOCATION:	Westbury Landfill
EASTING / NORTHING:	388171.31 / 152934.27
ELEVATION:	64.60 mOD
DRILLED BY:	WME & Well Head Drilling
LOGGED BY:	Tristan Rees-White
DATE STARTED	18th September 2003
DATE COMPLETED:	17th November 2003

DRILLING INFORMATION

DRILLING TYPE:	Rotary / Shell & Auger	
WELL DIAMETER:	300mm	
CASING DIAMETER:	168mm OD / 150mm ID	
SCREEN TYPE:	Stainless steel wire-wrap	
SLOT SIZE:	1.0mm	
FILTER PACK:	1.0 - 1.6mm filter sand	
WATER STRUCK (BGL):	7.80 - 8.20m	▽
FINAL WATER LEVEL:	7.72m	▽

DEPTH | BOREHOLE CONSTRUCTION | INTERPRETED LITHOLOGY | LITHOLOGICAL DESCRIPTION



TOPSOIL

CLAY COVER

CKD

Dry, friable CKD, becoming wet with depth.

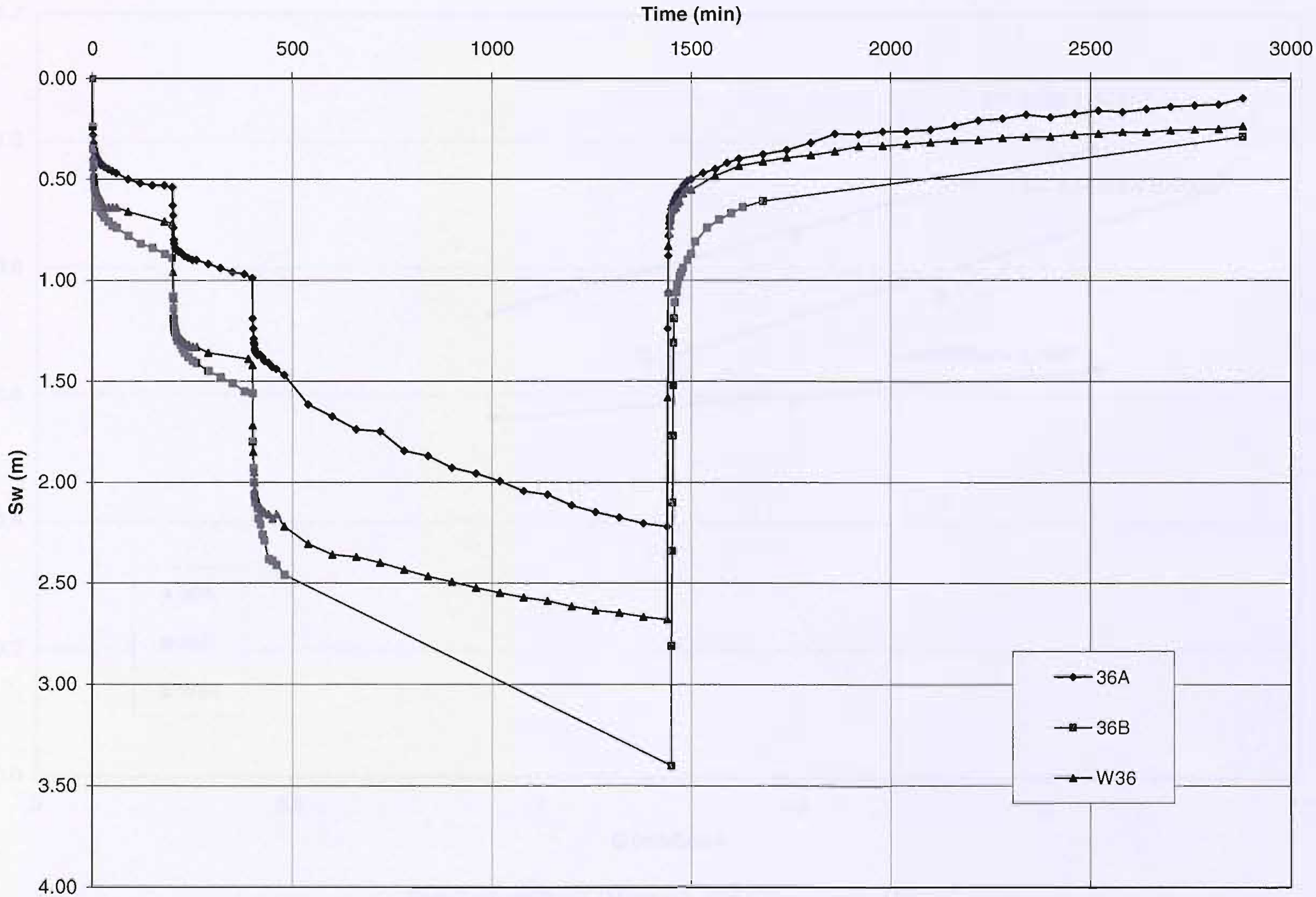
Saturated, gravely sandy clay.

CKD. Dry to damp. Soft and friable.

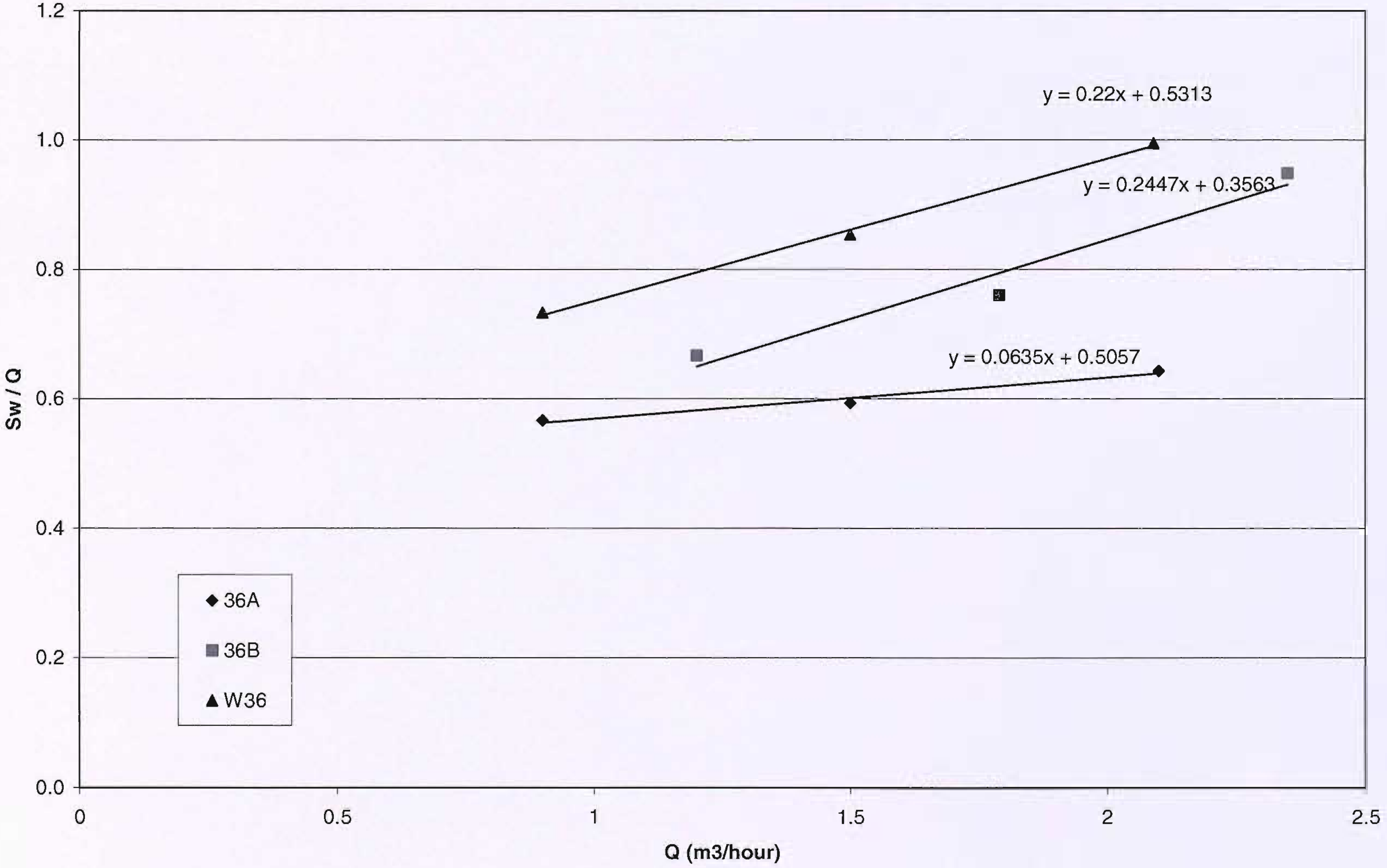
CKD

Hard horizon in CKD.

CLAY. Dark grey/blue to orange at base, v shelly, v firm virgin clay.



Step test data, Westbury landfil



Step test analysis (Hantush and Bierschenk, 1963)