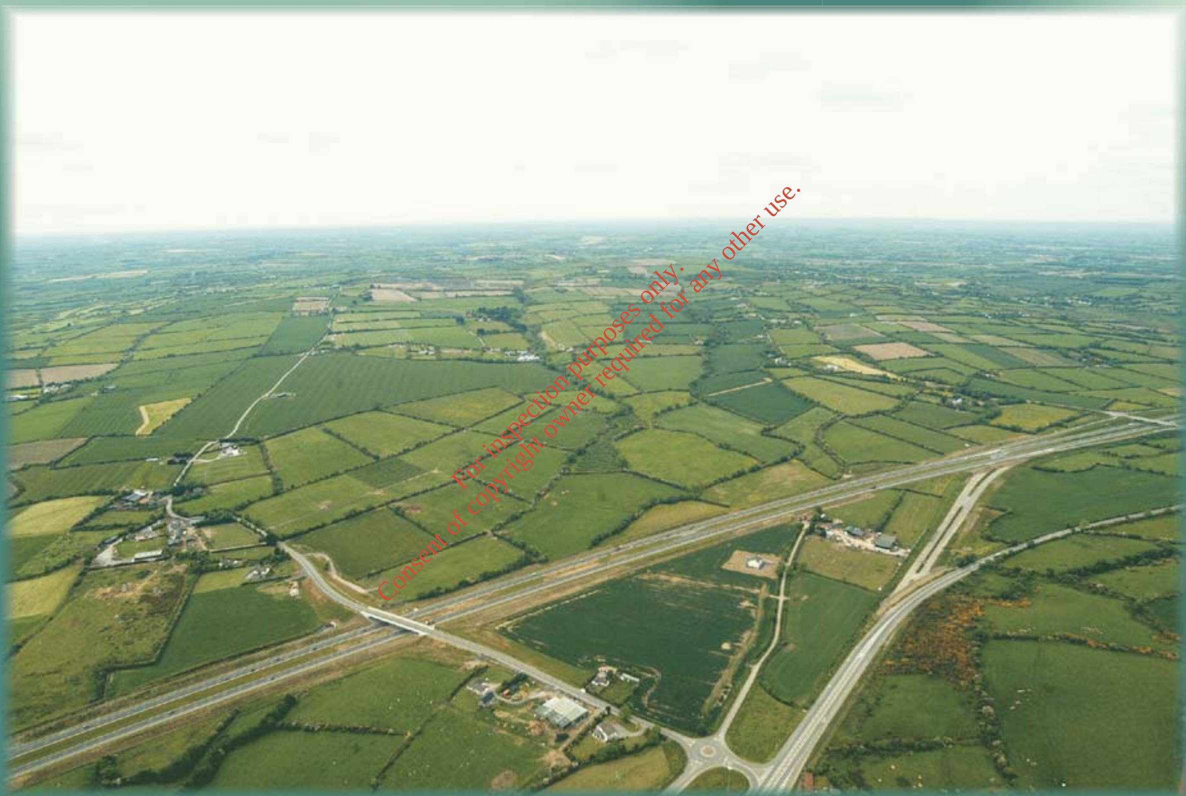
Fingal County Council
Comhairle Contae Fhine Gall

Fingal Landfill Project



Hydrogeological Risk Assessment

Waste Management Plan
Working for the Dublin Region

February 2009

RPS

EXECUTIVE SUMMARY

Terms of reference

At the request of the EPA, in their letter dated 17th October 2008, a detailed quantitative probabilistic risk assessment has been undertaken in order to examine in detail the fate and transport of contaminants within the leachate and risk to groundwater based on consideration of environmental setting and proposed engineering methods at the site.

Approach

This Assessment has been carried out in accordance with the Environment Agency (England and Wales) Guidance on "*Hydrogeological Risk Assessment for Landfills*" which was designed to ensure that landfills meet the requirements of the Groundwater Directive with respect to discharge of List I and List II substances.

The Guidance advocates a risk based tiered approach comprising, Problem Formulation, Risk Screening, Simple Risk Assessment and Complex Risk Assessment. This report comprises a Complex Risk Assessment. The lower tiers of assessment have previously been undertaken as part of pre-planning studies and the EIA process and have concluded that the proposed landfill does not present a significant risk to groundwater beneath the site.

Hydrogeological Conceptual Model

A hydrogeological conceptual model has been developed based on intrusive sub-surface investigations, groundwater monitoring and the outline design of the proposed landfill and is summarised as follows:

- The landfill is underlain by Glacial Till comprising low permeability clay over localised sand and gravel deposits over limestone bedrock. The low permeability clay will have minimum thickness of 10 m beneath the landfill footprint following excavation.

- The groundwater levels within the sand and gravel deposits (where present) are generally the same as in the limestone bedrock. The limestone bedrock and the sand and gravel deposits are in hydraulic continuity with each other and form a single aquifer unit.

- Groundwater within the aquifer unit is confined by the overlying low permeability clay. The potentiometric surface within the aquifer unit generally follows the topographic gradient with levels being close to the current ground surface in the north-west of the proposed landfill foot print. To the north of the proposed footprint artesian conditions exist.

- Perched groundwater is present within the clay subsoils. The perched groundwater levels within the clay are generally higher than the potentiometric surface within the aquifer unit with the exception of the far north of the proposed foot print where artesian levels exist and the potentiometric levels are approximately 1 m above ground level and 1-2 m above the perched water level within the clay. Therefore with the exception of the northern area of the footprint there is a vertical downward gradient from the clay to bedrock

- Leachate levels will be maintained at a maximum level of 1 m above the base of the composite liner system. Perched groundwater within the clay subsoils is generally expected to be above the level of leachate within the landfill creating an inward gradient into the landfill.

Source – Pathway - Receptor Linkages

The potential **source** of pollution is contaminants within landfill leachate. The concentration of contaminants within leachate is dependant upon waste type and will decline overtime due to degradation of compounds, dilution by infiltrating water and losses to the vapour phase.

The environmental **receptor** considered is the groundwater body below the site within the bedrock and sand and gravel deposits (where present).

The **pathways** by which contaminants within leachate could reach the receptor comprise a number of different media components, transport mechanisms and attenuation processes as follows.

Pathway Media	Contaminant Transport Mechanisms	Attenuation Processes
HDPE Liner	Direct Leakage through damage or defects or as result of degradation of liner	Declining source term. Dilution of leachate by rainwater infiltrating waste. Degradation of contaminants within leachate
Mineral Liner (vertical pathway)	Advection or Diffusion	Retardation, Dispersion
Clay subsoil (vertical pathway)	Advection or Diffusion	Retardation, Dispersion and Degradation
Aquifer unit (Horizontal pathway/saturated zone)	Advection	Dilution, Retardation, Dispersion and Degradation

Modelling Approach

A quantitative Hydrogeological Risk Assessment has been undertaken using the following software to implement the approach.

- *LandSim Version 2.5 (Golder Associates, 2007)*
- *Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0 (EA, 2004)*

Both advection and diffusion are possible contaminant migration mechanisms throughout the lifecycle of the landfill. The dominant mechanism depends on the relationship between leachate levels and external hydraulic heads within the in-situ clay subsoils and the underlying aquifer unit. As a conservative simplification both mechanisms have been modelled separately for the entire lifecycle of the site up to 20,000 years. This will reflect the worst outcomes of both mechanisms in isolation, independent of which migration mechanism is dominating at a specific place or time within the landfill during the modelled lifetime of the site.

LandSim is used to predict leachate concentrations and elevations during the operational phase of the site and to estimate advective fluxes from the landfill when leachate heads exceed groundwater levels in the surrounding clay subsoils and the potentiometric surface in the aquifer unit.

The Environment Agency's '*Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0'* has been used to predict concentrations of the priority contaminants at their respective compliance points, through the process of diffusion when leachate heads are below groundwater levels in the surrounding subsoils.

Selection of Input Parameters and Probabilistic Assessment

The input parameters for the model are based on site specific data where available and have been selected to be conservative.

Uncertainty within the selection of input parameters is addressed by the use of a probabilistic approach which allows the input parameters to be entered as ranges. The results are also returned as ranges and defined according to the probability of occurrence. The 95th percentile values are used as outputs from the model, which are representative of the reasonable worst-case performance of the landfill.

The compliance point for List I substances is considered to be the base of the in-situ clay subsoils prior to dilution within the aquifer unit. The compliance point for List II substances is considered to be a theoretical monitoring point 100 m down-gradient of the proposed waste footprint within the application boundary.

Results

- For both the advective and diffusive scenarios no breakthrough of List I or List II substances are predicted during the theoretical managed lifetime of the site i.e. within 60 years of the start of landfilling;.

- Cadmium is the only List I substance to record breakthrough at the compliance point within the modelled lifetime of the site of 20,000 years. The predicted 95^{th} percentile concentration of $1.14x10^{-5}$ mg/l, is not detectable with current laboratory methods and is only 1.14% of the minimum reporting value of 0.001 mg/l.

- None of the List II substances record peak concentrations greater than 10% of their respective guidelines within the modelled lifetime of the site of 20,00 years for either an advective of diffusive transport scenario. The predicted concentrations are sufficiently low that none of these contaminants will have a discernible impact upon groundwater quality within the aquifer unit.

- Chloride is the only determinant which may record detectable concentrations down-gradient of the landfill during the theoretical managed lifetime of the site. The predicted concentrations are below guideline and background concentrations and will not present a risk to groundwater.

Conclusions

The detailed, conservative and probabilistic risk assessments have shown that the proposed engineered landfill, situated within a low environmental risk setting within low permeability clay subsoils, will not result in deterioration in groundwater quality in the aquifer unit beneath the site. The proposed Landfill does not, therefore present a risk to groundwater and does not contravene the requirements of the Groundwater Directive.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES

1 INTRODUCTION

1.1 TERMS OF REFERENCE

The proposed Fingal Landfill development will comprise of a new fully engineered landfill at a greenfield site in north County Dublin. At the request of the Environmental Protection Agency (EPA), in their letter of 17 October 2008, RPS has, on behalf of the applicant, Fingal County Council, undertaken a probabilistic quantitative hydrogeological risk assessment for the proposed landfill.

1.2 OBJECTIVES

The overall objective of this report is to meet the requirements of the EPA as stated in their letter of 17th October 2008 and summarised as follows:

- Evaluate the potential for leachate leakage and migration to groundwater within the aquifer unit beneath the site;
- Predict concentrations of List I and List II substances (as defined in the EU Groundwater Directive 80/68/EEC) likely to be present in any potential leachate leakage; and
- Evaluate the significance of potential impacts from leachate on groundwater receptors by comparison with relevant quality standards or background concentrations

1.3 RISK ASSESSMENT APPROACH

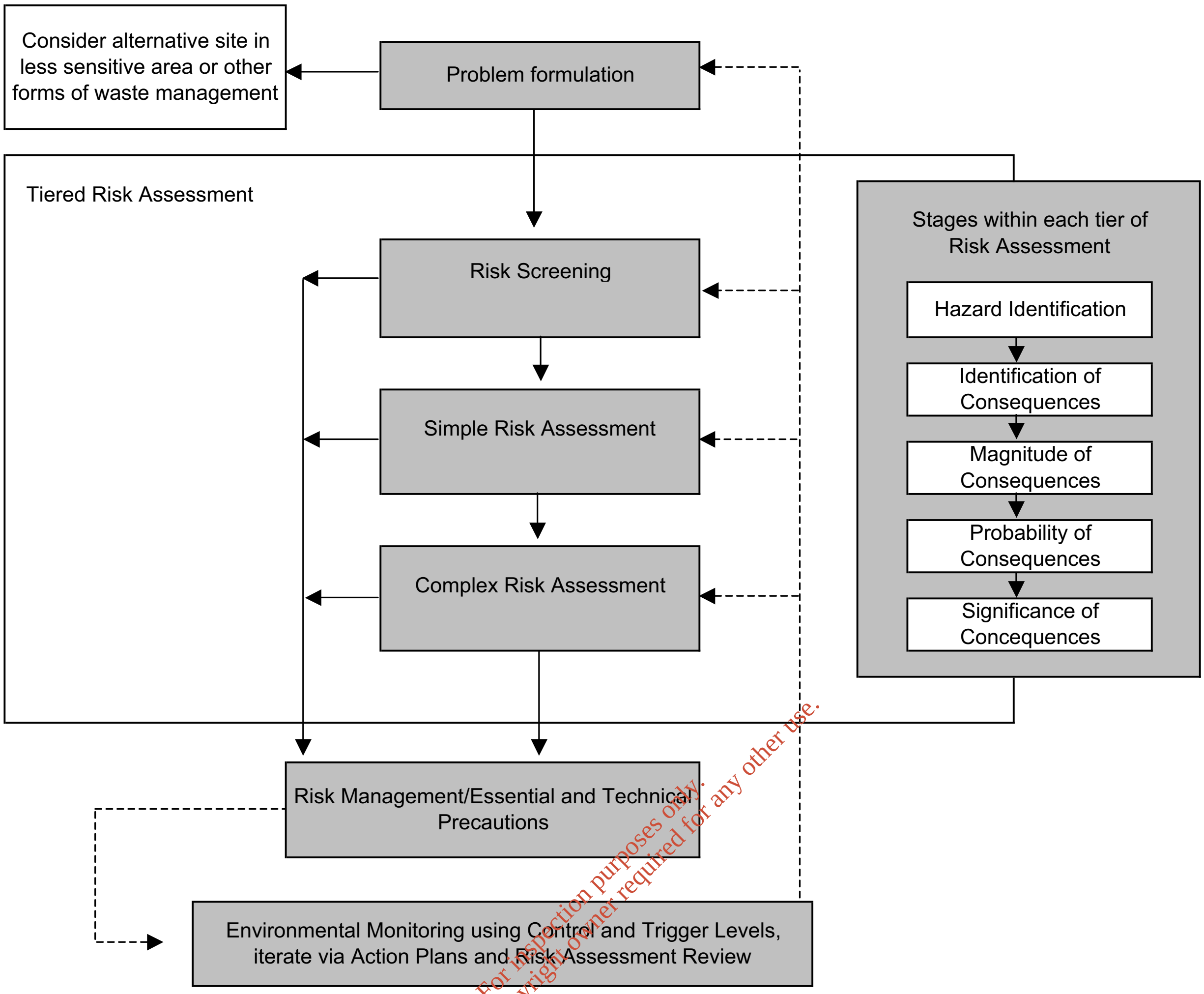
The assessment of risks to groundwater presented by the proposed landfill has been undertaken in accordance with the *Environment Agency (England and Wales) Guidance on Hydrogeological Risk Assessments for Landfills (March 2003)* which provides a framework for a tiered approach to risk assessment.

This approach is illustrated in **Figure 1**.

A number of these stages have already been undertaken. Problem formulation was undertaken as part of the pre-planning studies including the site selection. Risk screening was undertaken as part of the EIA process using the Groundwater Response Matrix for Landfills published by the GSI, EPA and DoEHLG. This identified that based on the classification of the underlying aquifer and the vulnerability rating (which is dependent on the thickness of sub-soils beneath the site and the permeability of those subsoils) the site had an R1 response for suitability for landfill development, which is the lowest possible rating. The development would of course be subject to the EPA landfill Design Manual and conditions of a waste licence. The EIS presented a preliminary risk assessment comprised of a conceptual model which identified the site as presenting an imperceptible risk to groundwater.

A "Simple Risk Assessment" in the form of leakage and dilution calculations were presented in January 2007 in response to further information requested by the EPA under Article 14(2)(b)ii of the Waste Management Regulations. This assessment indicated that the risk presented to groundwater from leakage of leachate was low based on the significant dilution factor and did not take account of attenuation processes beneath the site.

Figure 1 Framework for Tiered Approach to Risk Assessment



After (UK Environment Agency) Hydrogeoloical Risk Assessments for Landfills, 2003

As described in section 1.2, above a detailed quantitative probabilistic risk assessment has been undertaken, at the request of the EPA, in order to examine in detail the fate and transport of contaminants within the leachate to groundwater based on consideration of environmental setting and proposed engineering methods. A conceptual model has been developed using a source pathway receptor approach to identify the processes whereby contaminants may impact upon identified receptors. This approach has been implemented using proprietary software consisting of *LandSim Version 2.5* and the *Contaminant Fluxes from Hydrualic Containment landfill spreadsheet v1.0* produced by the Environment Agency (England and Wales). This constitutes a "Complex Risk Assessment" which is the subject of this report.

The EA Guidance on Hydrogeological Risk Assessment for Landfills was developed to ensure that landfills are satisfactorily designed to meet the requirements of the Groundwater Directive 80/68/EEC which provides that *"Member States are obliged to take the necessary steps to:*

(a) prevent substances in List I from entering the groundwater: and

(b)limit the introduction of List II substances into groundwater so as to avoid pollution.

The current Groundwater Directive (80/68/EEC) will be replaced by Directive 2006/118/EC on the Protection of Groundwater against Pollution and Deterioration as a daughter directive under the Water Framework Directive. The new directive will seek to distinguish between hazardous substances, inputs of which should be prevented from entering groundwater and other pollutants, inputs of which should be limited from entering groundwater and to define threshold concentrations for other particular contaminants. At this time "hazardous substances" are considered to comprise List I and "other pollutants" comprise List II.

2 SITE SETTING

2.1 LOCATION AND TOPOGRAPHY

The landfill will be located in north County Dublin approximately 25km north of Dublin city, approximately 8km west-southwest of the town of Skerries and approximately 3.5km northwest of the town of Lusk. The site is bounded to the east by the M1 motorway and dissected by a tertiary road. The centre of the site is at OS grid reference 317674E, 257047N.

The topography of the study area is gently sloping from the west-northwest to east-southeast from an elevation of 70 m above Ordnance Datum (AOD) in the northwest to approximately 30 mAOD at Ballystrane in the southeast. Regionally, ground elevations rise to a high of 176 mAOD to the northwest. To the northeast of the study area across the M1 motorway the ground rises to a maximum height of 94 mAOD.

A relatively high density of streams lies in the area and follows the same WNW-ESE trend along the topographical slope draining the higher ground to the west.

2.2 SITE HISTORY

Land use in the area is primarily agricultural. Within the application boundary, the land is predominantly used for arable and dairy farming. During the baseline assessment conducted as part of the Environmental Impact Assessment (EIA) process, an area where waste was previously disposed was identified towards the south east corner of the application site. This historic landfill occupies a former sand and gravel pit and was operated in the late 1990s and closed at the turn of the century. This historic landfill will be subjected to a separate risk assessment process using the Environmental Protection Agency's Code of Practice for Unregulated Waste Disposal Sites (and in line with conditions in any Waste Licence issued by the EPA in respect of the site) to determine whether it can be remediated in-situ by construction of an engineered cap or whether excavation of material is required.

2.3 PRIOR INVESTIGATION AND ASSESSMENT

Detailed site investigations were carried out as part of the EIA process to determine the exact geological and hydrogeological characteristics of the site. Intrusive work has included:

- Drilling of 102 boreholes;
- Excavation of 27 trial pits; and
- Installation of a groundwater monitoring network involving the collection of time series data from 79 no. boreholes.

2.4 GEOLOGY

Bedrock geology beneath the landfill footprint has been mapped as Carboniferous limestone, siltstone and mudstone of the Loughshinny, Naul and Lucan Formations by the Geological Survey of Ireland

(GSI). There are two major fault zones within the general environs of the proposed site, the North Dublin Fault that runs approximately east-west located to the north at the Bog of the Ring and a north-south fault that generally runs along the M1 Motorway in the area.

The subsoil beneath the study area has been found to be Glacial Till comprising sandy gravelly clay, with sand and gravel in places below the Glacial Till subsoil. Thickness of subsoil is variable across the area and the landfill footprint has been deliberately located in an area where thick (generally of the order of 20-27m) low permeability Glacial Till is present.

Sand and gravel deposits vary across the study area with thicknesses ranging from absent to greater than 10m.

2.5 HYDROGEOLOGY

2.5.1 Aquifer Units

The three bedrock formations underlying the footprint have been classified as being **Locally Important Aquifers** by the Geological Survey of Ireland (GSI). A letter from Dr Andy Sleeman of the GSI, dated 19th December 2006 confirmed that these formations are quite similar and differ only slightly in proportions of limestones and mudstones and therefore they will act as a single hydrogeological unit, with minor changes in lithology having negligible effect on groundwater behaviour which is much more likely to be influenced by faulting and fracturing of the rocks.

The Eastern River Basin District (ERBD) project, carried out under the Water Framework Directive has designated two groundwater bodies underlying the immediate area: the Hynestown and Lusk-Bog of the Ring. The Lusk-Bog of the Ring groundwater body underlies the footprint and extends to a total area of $86km^2$. The groundwater body is described as a bedrock groundwater body comprised of Dinantian impure limestone and 5% Dinantian pure bedded limestone.

The Quaternary sands and gravels which are locally present above the bedrock are not classified as a distinct aquifer by the GSI. The sands and gravels do however provide additional storage to the underlying bedrock aquifer. The clay overlying the bedrock and gravel deposits is considered to be a non-aquifer. However, there is perched groundwater within this layer.

2.5.2 Aquifer Properties

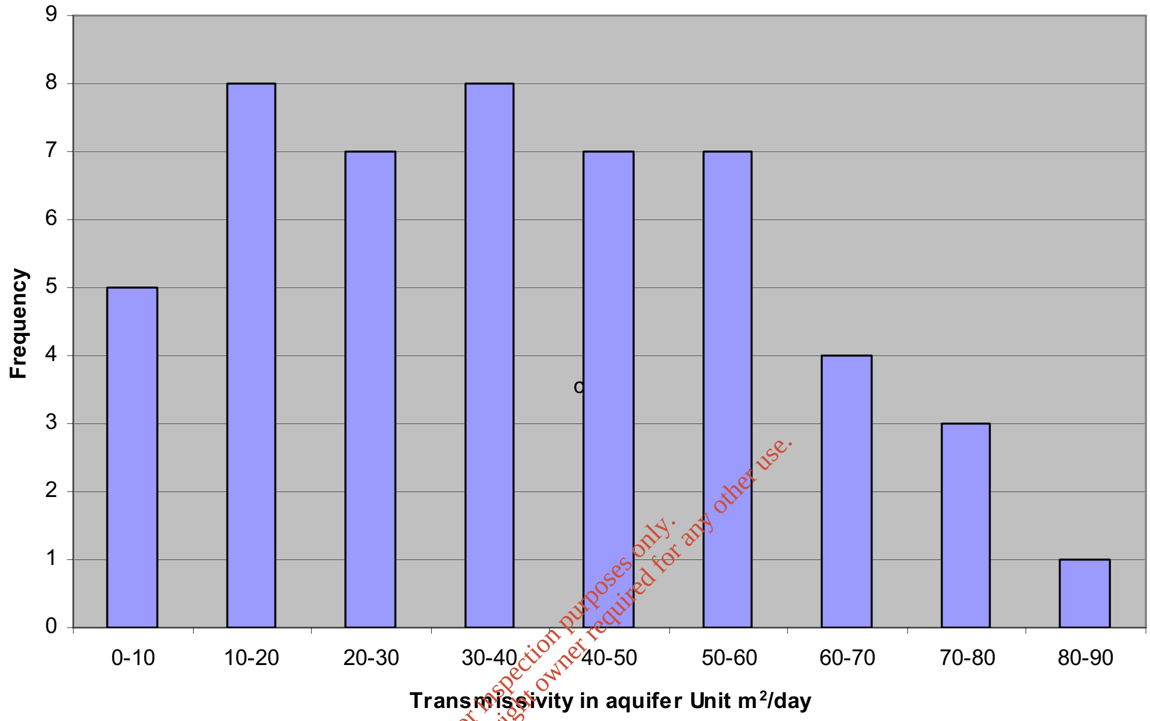
A number of boreholes have been drilled across the proposed footprint of the landfill. The bedrock aquifer thickness is at least 35m, the full thickness is not known. Fractures in the bedrock appear to be close to very closely spaced throughout the explored section, in places the rock has been described as completely shattered. Gravel thickness below the footprint of the site is variable ranging from absent to 10.7m.

Pumping tests have been conducted to assess the characteristics of the bedrock and gravel. Pumping tests have been carried out within four wells in the landfill study area. Three wells were drilled approximately 10m into the bedrock aquifer and the fourth was installed within the gravel deposits. Transmissivity values obtained for the bedrock range between 10 and $76m^2$/day. Higher transmissivity and storativity values were obtained near to the north-south trending fault.

Apart from one borehole, the storativity values are relatively low (1.9e-4 to 3.2e-3) and are consistent with a confined aquifer in which both the aquifer matrix and water are compressed.

Transmissivity within the gravel aquifer was found to range from 71-86m^2/day. This compares to the high end of the range obtained for the bedrock aquifer but lower than expected for a clean gravel, suggesting there is a significant fines content. Storativity is also within the range obtained for the bedrock and is indicative of a confined aquifer response. The frequency distribution of transmissivity values within bedrock and sand and gravel is presented in **Figure2**.

Figure 2 Frequency Distribution of Transmissivity Values in Bedrock and Sand and Gravel



2.5.3 Groundwater Flow

Groundwater flow in the bedrock is primarily along faults and fractures. Groundwater levels within the bedrock aquifer, sands and gravels and the clay subsoils have been measured once every month decreasing to once every three months over two and a half years (from June 2005 to November 2007). Plots of groundwater contours within the fractured bedrock aquifer show that groundwater flows within the fractured bedrock beneath the application area in a southeasterly direction along the general topographical gradient. Water levels in the bedrock aquifer vary from approximately 52 mAOD in the northwest corner of the footprint to 29 mAOD in the southeast corner of the footprint.

Groundwater in the bedrock aquifer is confined by the overlying low permeability clay subsoils. In areas of low lying topography, notably to the north and east of the proposed landfill footprint, the potentiometric surface within the bedrock aquifer is above ground level, therefore giving rise to artesian conditions.

The hydraulic gradient has been calculated from measured groundwater levels. The hydraulic gradient varies across the footprint being steepest along the western boundary and at its most shallow in the southeast. The average hydraulic gradient across the site is approximately 0.3.

Vertical groundwater movement between the overburden and the bedrock has been considered using groundwater level data from monitoring wells installed in the different hydrogeological units.

Groundwater levels within the clay subsoils beneath the footprint are generally above the potentiometric level in the gravels. Heads within the clay subsoils are approximately 2 m to 10 m above those in the gravels; this indicates a downward gradient between the overlying clay and the underlying formation.

The potentiometric surface within the gravel deposits is generally at the same elevation as the potentiometric surface in the bedrock indicating that there are no vertical gradients between the two units. The exception to this is in the east of the application site where groundwater levels in the bedrock are 0.25m higher than in the overlying gravels, this suggests a vertical upwards hydraulic gradient from the bedrock to the gravel. The difference in measured groundwater levels in the different horizons is demonstrated in **Figures 3 a, b and c** which present hydrographs based on manual measurements of groundwater level at three locations around the periphery of the site. The bedrock and the gravel are therefore considered to be in hydraulic continuity with each other and have been considered as a single hydrogeological unit.

Recharge to the aquifer unit across the proposed footprint is low due to the thickness and low permeability nature of the clay subsoils. The hyrdrographs (Figures 3a-c) show fluctuation in the water level within the clay which is not reflected within the limestone bedrock or gravel.

Figure 3a. Groundwater Levels to North-west of Proposed Footprint

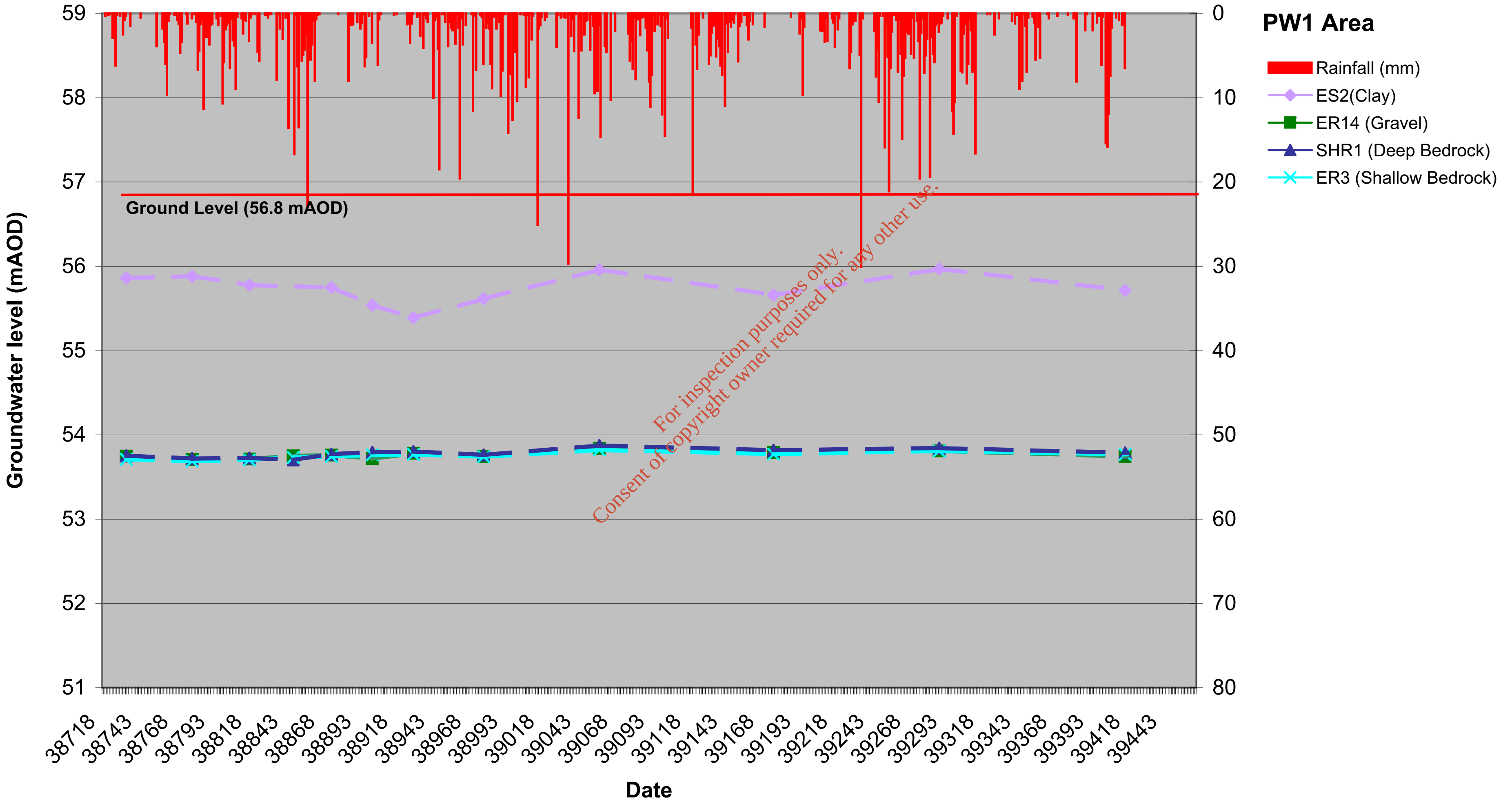


Figure 3b Groundwater Levels to East of Proposed Footprint

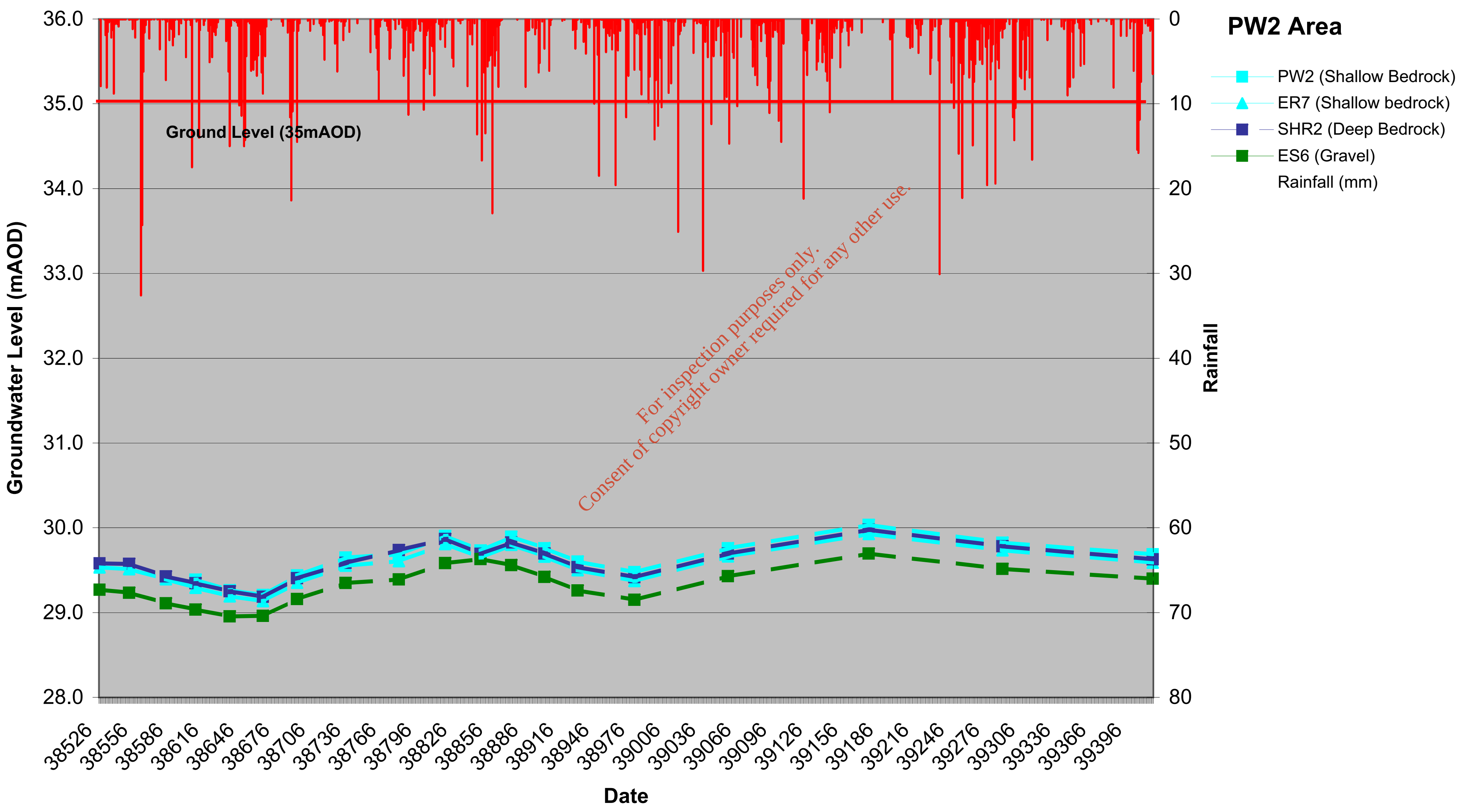
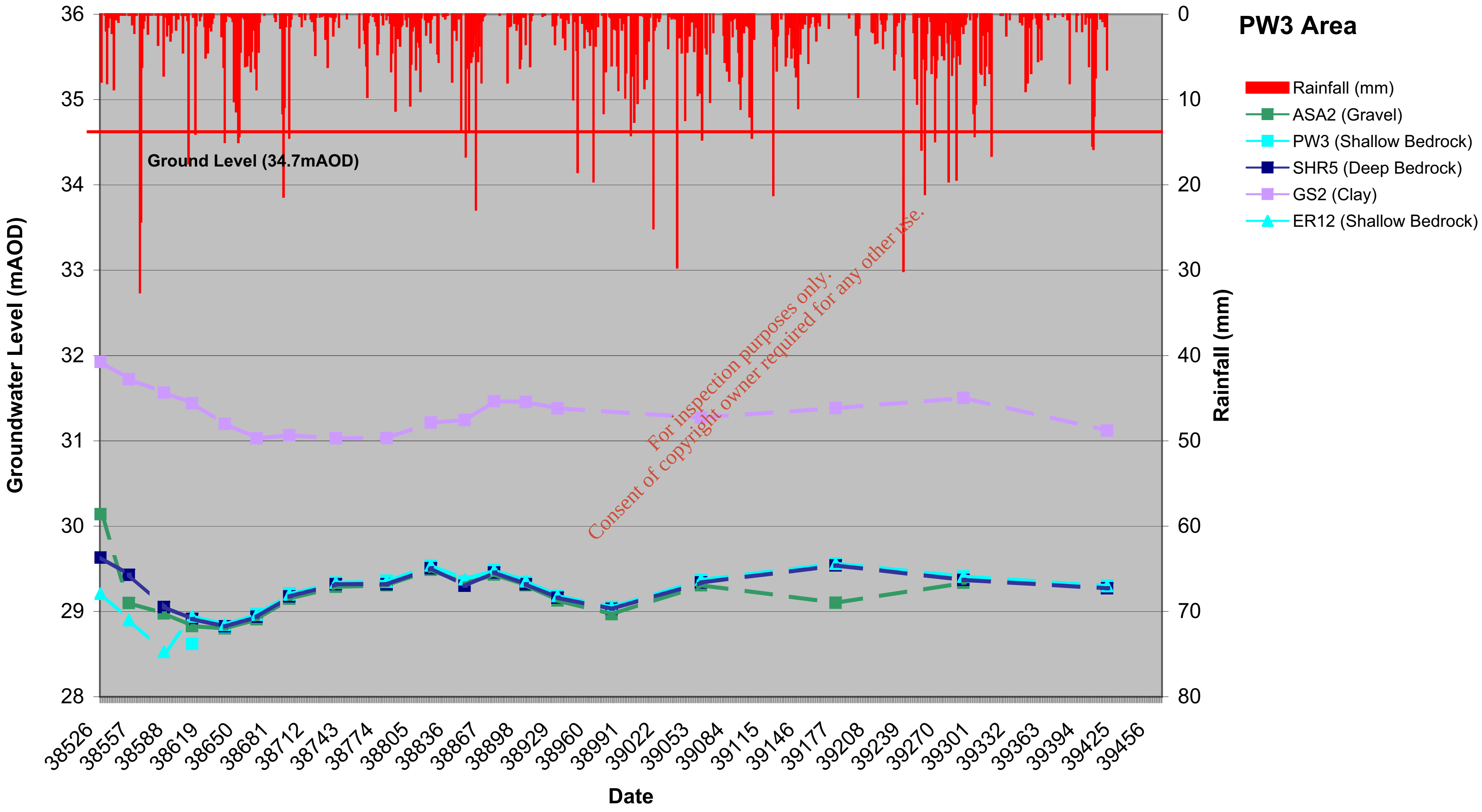


Figure 3c Groundwater Levels to South-East of Proposed Footprint

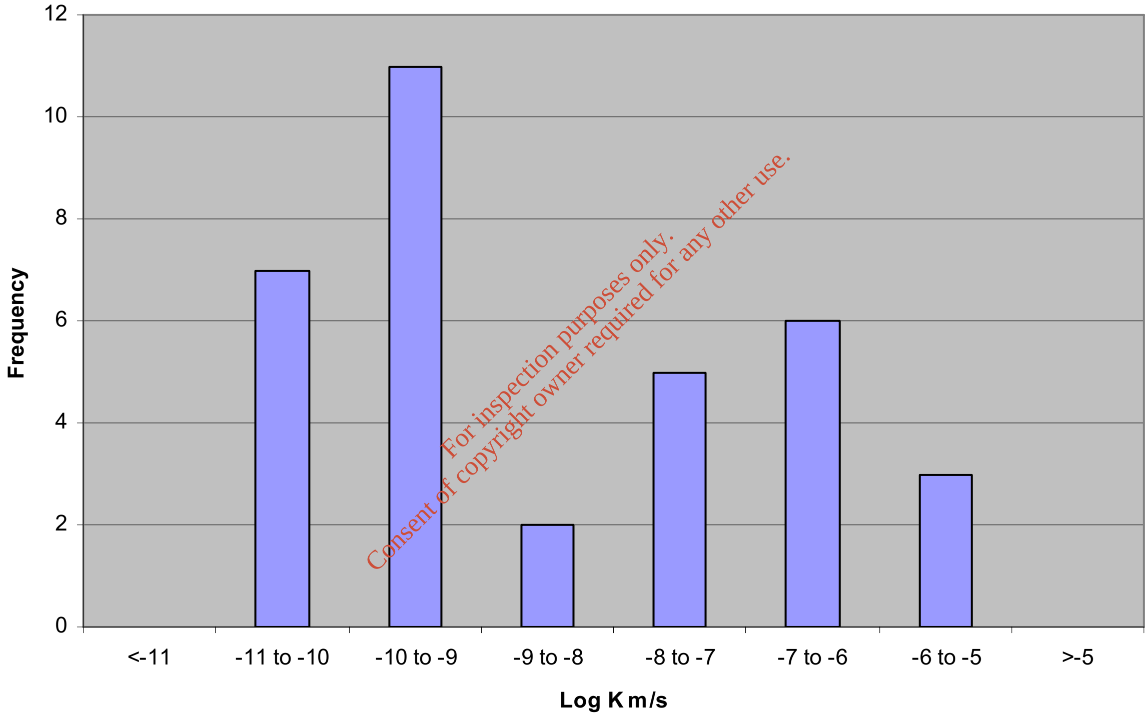


2.5.4 Water in Clay Subsoils

Water is present within the clay subsoils beneath the site. The water levels in the clay measured in standpipes across the site range from approximately 56 m AOD in the north-west of the site to 31 m AOD in the south-east of the site.

Hydraulic conductivity values of the clay have been measured using variable head tests and triaxial permeability tests; results gave a minimum value of $3.8x10^{-11}$ m/s, a maximum of $5.3x10^{-6}$m/s and a median of $8.19x10^{-10}$ m/s. A frequency distribution plot of the log hydraulic conductivity (log k) values within the clay subsoils is presented as **Figure 4**. These values relate to material that is within or close to the footprint of the landfill following excavation to form the landfill void. The frequency distribution show that more than half of the data obtained is within the range $1x10^{-11}$ m/s and $1x10^{-9}$ m/s.

Figure 4 Frequency Distribution of Log K Values in Clay



Based on the range of permeabilities measured from the various techniques the material is classed as predominately low to very low permeability clay

3 PROPOSED LANDFILL CHARACTERISTICS

3.1 CONSTRUCTION AND MANAGEMENT PROPOSALS

The proposed development of the landfill facility covers an area of approximately 210 hectares and comprises two distinct areas:

- Buffer zone consisting of landscape/screening/infrastructure areas; and
- Waste disposal area

The waste disposal area will cater for up to 9,400,000 tonnes of waste over its lifetime. The area will consist of approximately 20-25 individual cells each with approximate areas of 2.5 ha (25,000m^2), each will hold on average 400,000 tonnes of waste and it is anticipated that it will take between 1 and 1½ years to fill each cell with the initial cells possibly being filled in less than a year. The cells will be developed and restored on a phased basis from a south to north direction; it is proposed that there will be up to 11 phases of cell development with capping being carried out on a rolling basis as cells are filled.

The proposed landfill is designed to contain the leachate produced so that discharges of List I and List II substances contained within the leachate are restricted from entering groundwater and thus do not contravene the Groundwater Directive. The main components of the landfill engineering are described in the following sections.

3.2 CELL CONSTRUCTION

Prior to each phase of cell development additional site investigation will be conducted. This is so further information on specific development areas can be retrieved. This information will be of use in the detailed design of each phase. Information such as depth, stiffness and permeability of the glacial tills is of importance as is the examination of the re-usability of the Clays in the composite lining and/or capping systems. A key aim of the phased site investigations will be to identify the depth of clay over the underlying aquifer and give enough information to the design process to ensure that a minimum of 10m of clay is left in-situ after the base depth of the cells is excavated.

3.2.1 Composite Lining System

A composite lining system will be installed at the landfill and will consist of the following components at a minimum:

- A minimum 0.5m thick leachate collection system;
- Geotextile protection layer;
- A minimum 2mm thick HDPE liner or equivalent; and
- Compacted clay liner with a permeability ≤ $1x10^{-9}$ m/s and a thickness of 1m or equivalent.

The composite liner system will be designed to act as the primary barrier to leachate migration. The lining system will be further supported by a minimum thickness of 10m in situ low permeability clay subsoil.

3.2.2 Control Drainage Layer

Where required a control drainage layer will be installed under the liner system so that any groundwater released from the clay (subsoil) can be pumped during construction and initial filling of the cells in order to minimise the risk of any potential basal heave from upward groundwater pressures. The control drainage layer where required will consist of the following:

- Geotextile separation layer;
- Gravel layer incorporating slotted collection pipes, or equivalent; and
- Extraction from the drainage layer to the surface water management system.

3.2.3 Capping

An engineered low permeability compacted mineral layer will be placed across the completed landfill. The purpose of the cap is to minimise infiltration to the waste mass and therefore minimise the production of leachate. Routine inspections of the cap will be undertaken during the period of management control and repairs made as necessary.

In the event that the volumes of leachate produced at the site indicate that the cap is not performing as designed, the integrity of the cap will be checked and repairs made as necessary.

The final capping system will at a minimum consist of a:

- Gas collection layer;
- Compacted mineral layer ≥ 0.6m thickness with a permeability ≤ $1x10^{-9}$m/s or equivalent;
- Drainage layer ≥ 0.5m thickness having minimum hydraulic conductivity ≥$1x10^{-4}$m/s or equivalent;
- Subsoil; and
- Topsoil (the combined subsoil and topsoil will have a minimum thickness of 1m)

3.2.4 Monitoring

Following the end of the management period, groundwater and leachate monitoring will be continued to assess if the landfill is performing as designed. The appropriate control and trigger levels will be assigned to ensure performance is assessed to agreed limits. There will be no end to the management phase if agreed environmental objectives are not achieved.

3.2.5 Leachate Drainage Systems and Leachate Head Control

Leachate elevations within the landfill will be controlled artificially during the managed lifetime of the facility by use of a leachate collection system. Leachate levels will be continually controlled and maintained at a maximum level of 1m above the basal liner of the cells. As part of the licensing process, control of leachate levels will be maintained at the maximum of 1m of leachate head above the basal liner for the duration of the active lifetime of the site. Even when the site ceases to accept waste, the leachate control measures will be maintained until such time as it can be proven that no environmental risk exists from the leachate. Only at that point would the discontinuation of pumping from the cells be allowed.

4 CONCEPTUAL SITE MODEL

4.1 HYDROGEOLOGICAL CONTEXT

The main features of the hydrogeological system in relation to the proposed landfill are summarized below

- The current land surface beneath the proposed footprint currently slopes from north-west to south-east from approximately 60 m AOD in the north-west to approximately 38 m AOD in the south east corner of the site.

- The proposed landfill is underlain by Glacial Till comprising low permeability clay over localised sand and gravel deposits over limestone bedrock.

- The low permeability clay will have minimum thickness of 10 m beneath the proposed landfill footprint following excavation to maximum depth of 10 m.

- The groundwater levels within the sand and gravel deposits (where present) are generally the same as in the limestone bedrock. The limestone bedrock and the sand and gravel deposits are in hydraulic continuity with each other and form a single aquifer unit.

- Groundwater within the aquifer unit is confined by the overlying low permeability clay.

- The potentiometric surface within the aquifer unit generally follows the topographic gradient with levels ranging from approximately 52 m AOD in the northwest of the site to 29 m AOD in the southeast of the site.

- Potentiometric levels within the aquifer unit are close to the current ground surface in the north-west of the proposed landfill foot print and along the northern boundary of the footprint artesian conditions exist.

- Perched groundwater is present within the clay subsoils at elevations ranging from approximately 56 m AOD in the northwest of the site to 31 m AOD in the southeast of the site.

- The perched water levels within the clay are generally higher than the potentiometric surface within the aquifer unit. At some places within the proposed footprint the perched groundwater levels within the clay may be as much as 10 m above the potentiometric levels within the aquifer unit. The exception to this is in the far north of the proposed foot print where artesian levels exist and the potentiometric levels are approximately 1 m above ground level and 1-2 m above the perched water level within the clay. Therefore with the exception of the northern area of the footprint there is a vertical downward gradient from the clay to bedrock.

- Leachate levels will be maintained at a maximum level of 1 m above the base of the composite liner system. The composite liner will comprise an HDPE Liner over 1 m of compacted low permeability clay (engineered mineral liner) over 0.5 m of gravel drainage blanket (where required). The maximum head of leachate will therefore be approximately 2.5 m above the base of the excavation.

- Perched groundwater within the clay subsoils is generally expected to be above the level of leachate within the landfill creating an inward gradient into the landfill.

4.2 SOURCE-PATHWAY-RECEPTOR

4.2.1 Source

The potential source of pollution is contaminants within landfill leachate. The concentration of contaminants within leachate is dependant upon waste type and will decline overtime due to degradation of compounds, dilution by infiltrating water and losses to the vapour phase.

4.2.2 Receptor

The environmental receptor considered is the groundwater body below the site within the bedrock and sand and gravel deposits (where present).

4.2.3 Pathways

In order to reach the aquifer unit, contaminants must pass through the HDPE liner, through the engineered mineral liner and through 10 m of low permeability in-situ subsoils. The potential pathways by which this can occur are as follows:

1) Leakage through defects within the HDPE liner

2) Advective flow through engineered mineral liner driven by difference in leachate head within landfill and perched groundwater level within subsoil

3) Migration of contaminants through the engineered mineral liner from high to low concentration through the process of diffusion

4) Advective flow through the in-situ clay subsoils driven by the difference between the level of perched groundwater within the subsoils and the potentiometric surface within the bedrock aquifer

5) Diffusion of contaminants through the in-situ clay subsoils to bedrock aquifer from high to low concentration.

A combination of these pathways is required in order for contaminants to reach the bedrock aquifer, the principal mechanisms of transport will depend upon the relative elevations of leachate levels within the landfill, perched groundwater within the clay sub-soils and the potentiometric surface within the bedrock aquifer.

Leakage through the HDPE liner (1) will occur due to damage or defects occurring during the construction and operational phase of the landfill, and long term deterioration.

Advective flow through the engineered mineral liner (2) will only occur when the leachate levels are greater than the perched groundwater level within the surrounding subsoils. Based on the data available it is considered that this scenario is unlikely to occur as perched groundwater levels within the clay will be above the level of leachate within the landfill during the operational lifetime of the site. Therefore during the operational lifetime of the site the principal transport mechanism through the engineered mineral liner will be via diffusion (3). However, if management of leachate levels were to cease then leachate levels would rise over-time and could potentially exceed perched groundwater levels within the clay subsoils at which point there would be an advective component of flow from the landfill across the engineered mineral liner into surrounding in-situ clay subsoils. Eventually a hydraulic equilibrium between leachate levels and perched groundwater would be established such that there would be no net hydraulic flux between the two and the main transport mechanism would be diffusion.

Once outside of the landfill contaminants have the potential to migrate through 10 m of low permeability sub-soils. Across the central and southern area of the site where the potentiometric surface in the bedrock aquifer is below the perched groundwater levels within the sub-soils, contaminants are able to migrate through the sub-soils via advective flow (4) and diffusion (5). The rate of advective flow will be controlled by the vertical permeability of the clay sub-soils which ranges from 3.8×10^{-11} m/s to 5.3×10^{-6}m/s, and the difference in hydraulic head between the perched water in the clay subsoils and the bedrock aquifer.

Diffusion can operate at the same time as advection and where clay permeability and driving head is low it will still be the most dominant transport mechanism, however in areas of lower vertical permeability and higher driving head it will become insignificant compared with advective flow. In the north of the site, where the potentiometric surface in the bedrock is above the perched groundwater levels within the clay, there is no downward advective component to the bedrock aquifer and therefore the only contaminant transport mechanism will be via diffusion (5). This would be the case regardless of leachate levels within the landfill.

The range of pathway scenarios likely to operate within the lifetime of the landfill are presented as a flow diagram within **Figure 5**, together with schematic sketches, **Figure 6,** to illustrate the processes at work during a managed and unmanaged scenario.

Upon reaching the aquifer unit the principal transport mechanism will be advective flow within the sand and gravel deposits (where present) and fractures and fissures in the bedrock. The advective flow rate will be controlled by the transmissivity of the aquifer unit and the regional hydraulic gradient. The advective flow velocities within the aquifer unit will be sufficiently large compared to diffusive flux rates that diffusion will become an insignificant transport mechanism.

Throughout the various pathway components contaminants will be subject to the following attenuation processes:

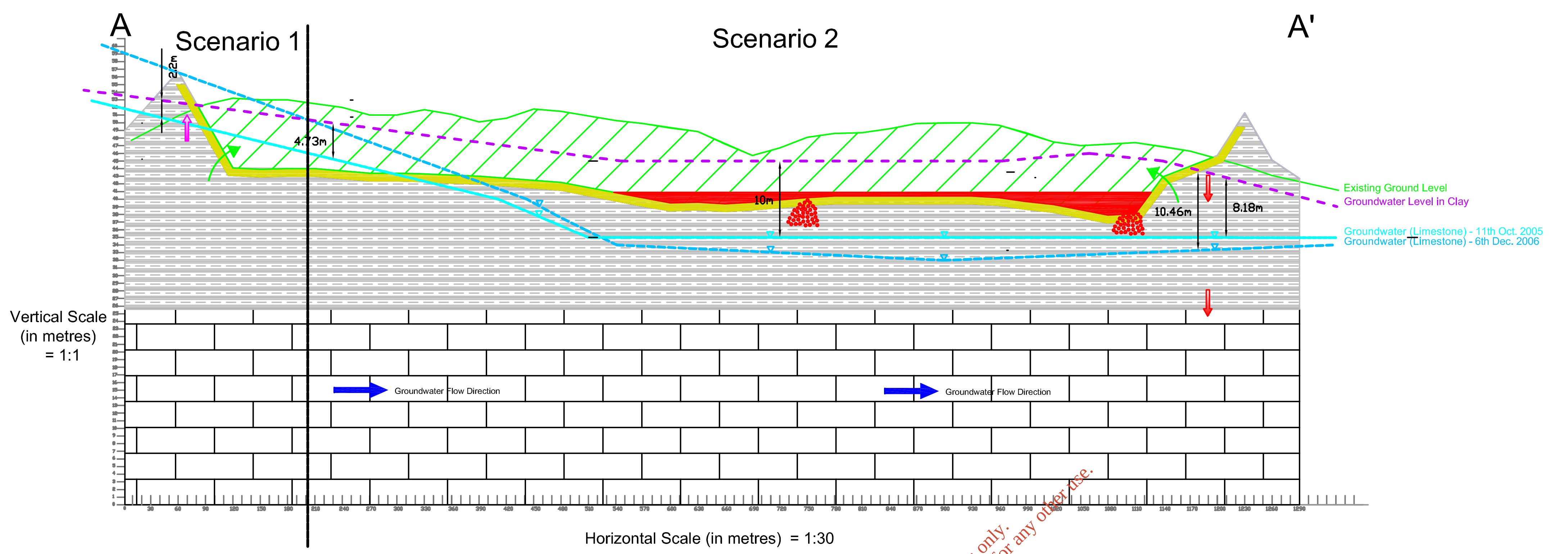
- ***Dilution*** by infiltrating rainwater or within receiving groundwater:
- ***Retardation*** by sorption processes within the pathway media (mineral liner, clay subsoils or aquifer unit);
- ***Dispersion*** due to physical characteristics of the pathway media; and
- ***Degradation*** and mass removal by chemical or biological processes within the pathway media

These processes are discussed in more detail in Section 5.5.

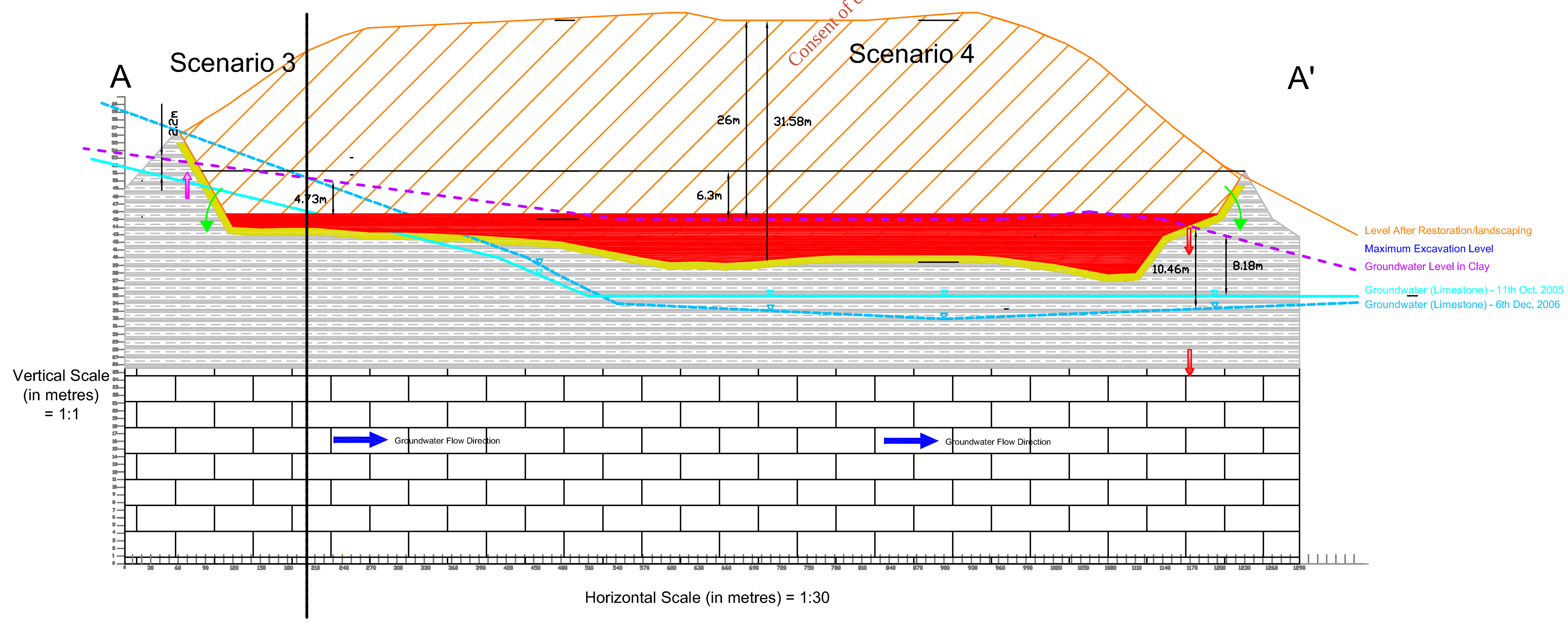
Figure 5 Potential Pathway Scenarios

		Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Assumptions	Leachate levels are **below** groundwater levels within the clay. Groundwater levels within the clay are **below** the potentiometric surface in the bedrock aquifer.	Leachate levels are **below** groundwater levels within the clay. Groundwater levels within the clay are **above** the potentiometric surface in the bedrock aquifer.	Leachate levels are **above** groundwater levels within the clay. Groundwater levels within the clay are **below** the potentiometric surface in the bedrock aquifer.	Leachate levels are **above** groundwater levels within the clay. Groundwater levels within the clay are **above** the potentiometric surface in the bedrock aquifer.
Source	Leachate	Declining source term within leachate determined by degradation of contaminants and dilution by infiltrating rainwater	Declining source term within leachate determined by degradation of contaminants and dilution by infiltrating rainwater	Declining source term within leachate determined by degradation of contaminants and dilution by infiltrating rainwater	Declining source term within leachate determined by degradation of contaminants and dilution by infiltrating rainwater
Pathway	HDPE liner	Leakage of leachate through defects in HDPE Liner	Leakage of leachate through defects in HDPE Liner	Leakage of leachate through defects in HDPE Liner/ complete deterioration of liner	Leakage of leachate through defects in HDPE Liner/ complete deterioration of liner
	Engineered Mineral Liner	Migration of contaminants through engineered mineral liner by process of **diffusion**.	Migration of contaminants through engineered mineral liner by process of **diffusion**.	**Advective** flow through engineered mineral liner driven by difference between head of leachate above liner and groundwater level within in-situ clay subsoils	**Advective** flow through engineered mineral liner driven by difference between head of leachate above liner and groundwater level within in-situ clay subsoils
	In-situ clay subsoil	**Diffusion** of contaminants through 10m of in-situ clay	**Advective** flow through 10 m in-situ clay driven by difference between groundwater level in-situ clay subsoils and potentiometric surface in aquifer unit. **Diffusion** will become significant if advective fluxes are low.	**Diffusion** of contaminants through 10m of in-situ clay	**Advective** flow through 10 m in-situ clay driven by difference between groundwater level in-situ clay subsoils and potentiometric surface in aquifer unit. **Diffusion** will become significant if advective fluxes are low.
Receptor	Aquifer Unit	Dilution within aquifer and **advective** flow to down gradient compliance point	Dilution within aquifer and **advective** flow to down gradient compliance point	Dilution within aquifer and **advective** flow to down gradient compliance point	Dilution within aquifer and **advective** flow to down gradient compliance point

OPERATIONAL PHASE

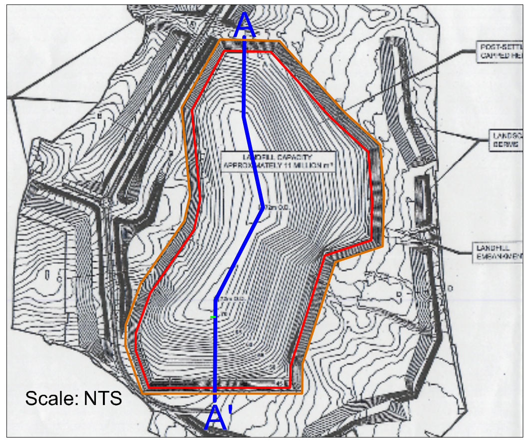


POST MANAGEMENT



Notes

- Landfill Clay Liner
- Clay
- Aquifer Unit (Limestone bedrock and sands and gravels, where present)
- Existing Material Removed before Landfill
- Added soil for Landscaping
- Clay Groundwater Level
- Limestone Aquifer Groundwater Levels
  - Groundwater (Limestone) - 11th Oct. 2005
  - Groundwater (Limestone) - 6th Dec. 2006
- Leachate
- Diffusion Across Boundary
- Advective Flow from Subsoil
- Advective Flow from Leachate
- Advective Flow from Bedrock



Rev:	Date:	Amendment:	Name:	Checked:
-	-	-	-	-

Drawing Based Upon: -

Status: Preliminary

Notes: Contractors are not to scale from this drawing. All dimensions to be checked on site and any discrepancies, ambiguities and/or omissions between this drawing and information given elsewhere must be reported to this office. If in doubt, ask.

RPS
Conrad House Beaufort Square Chepstow Monmouthshire NP16 5EP
T 01291 621821 F 01291 627827 E rpssw@rpsgroup.com W www.rpsgroup.com

Client: -

Project: Fingal Landfill EIS

Title: Conceptual Model - Operational Phase and Post Management Phase of Landfill

Date: 02.02.09 Scale: NTS Original Paper Size: A3

Drawn: RC Checked: LW /RG Job Ref: JER4201

Figure Number: 006 Rev: -

www.rpsgroup.com

Drawing Ref.JER4201-003_29.01.09_Conceptual Model showing Advective Flux

5 HYDROGEOLOGICAL RISK ASSESSMENT

5.1 MODELLING APPROACH

A "Complex Risk Assessment" has been undertaken in accordance with guidance issued by the EA on the "Hydrogeological Risk Assessment for Landfills" using proprietary software to implement the approach. The conceptual model has identified that there are three principal contaminant transport mechanisms: direct leakage through the HDPE liner; and advection and or diffusion through the engineered mineral liner and in-situ clay. It has therefore been necessary to use a combination of software tools, namely:

- *LandSim Version 2.5 (Golder Associates, 2007)*
- *Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0 (EA, 2004)*

LandSim is used to predict leachate concentrations and elevations during the operational phase of the site, including changes in infiltration, declining source term within leachate and deteriorating leachate control systems. LandSim is also used to measure advective fluxes from the landfill when leachate heads exceed groundwater levels in the surrounding clay subsoils and the potentiometric surface in the aquifer.

LandSim can be used to model the full lifecycle of a landfill. However, as LandSim does not account for the processes of diffusive flux it is not an appropriate model to predict impacts arising from the migration of contaminants throughout the entire lifecycle of the site. The Environment Agency spreadsheet is therefore used to predict these impacts at the same compliance points.

The Environment Agency's '*Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0'* has been used to predict concentrations of the priority contaminants at their respective compliance points, through the process of diffusion when leachate heads are below groundwater levels in the underlying clay subsoil and therefore hydraulically contained. Reference has been made to the Environment Agency publication '*Contaminant fluxes from hydraulic containment landfills – a review'* (*Ref. 1*) for guidance on the use of appropriate parameters.

This spreadsheet has been modified by RPS to allow a probabilistic assessment to be undertaken in the same way as LandSim. Palisade's @RISK software is used to allow ranges of input parameters to be specified rather than single values. Only contaminant attenuation within the clay liner is accounted for within the spreadsheet and therefore represents a further degree of conservatism in the assessment.

Both software models facilitate a stochastic analysis to account for the variability and uncertainty of the input parameters i.e. the input parameters can be entered as ranges.

The LandSim model identifies 20,000 years as the maximum reported time limit following commencement of waste tipping at a site. This is identified by the Environment Agency (England and Wales) as the total effective lifecycle duration of a landfill and is a non-user-defined parameter within Landsim. Accordingly, a period of 20,000 years has also been defined within the diffusion risk assessment as representing the maximum duration of the site.

5.2 SELECTION OF PARAMETERS

5.2.1 Overview

The input parameters for the model are based on site specific data where available. Parameters have been selected to represent a reasonable worse case scenario depending upon the transport mechanism being considered. The site specific data used to populate the model is presented in Table 5.1 together with its role within the risk modelling process.

Table 5.1: Site Specific Data

Data	Data Range	Derived from	Role within model
Engineering details	Various	Preliminary design as presented in EIS and Waste Application	Physical constraints of landfill.
Clay permeability	K ranges from 3.80×10^{-11} m/s to 5.3×10^{-6} m/s	Variable head tests, triaxial tests	Used to define rate of groundwater and leachate flow through clay
Water levels in clay, sand and gravel and bedrock	Clay: 31 to 56 m AOD Aquifer: 29 to 52 m AOD	Manual and automated groundwater measurements in standpipes installed within discrete horizons	Used to determine difference in hydraulic head between perched water in sub-soils and aquifer unit
Aquifer permeability	K ranges from 1.50×10^{-6} m/s to 1.7×10^{-4} m/s.	Analysis of pumping tests within the bedrock and gravels	Used to define rate of groundwater flow through the aquifer
Hydraulic gradient in aquifer	The average gradient measured is 0.032, the minimum is 0.016 and the maximum is 0.053	Data from representative monitoring rounds undertaken in June, September and December 2005 and March 2006.	Used to define rate of groundwater flow through the aquifer

Where no site specific data is available input parameters for the model are based on literature sources. Literature data used to populate the model is presented in Table 5.2 together with its role within the risk modelling process.

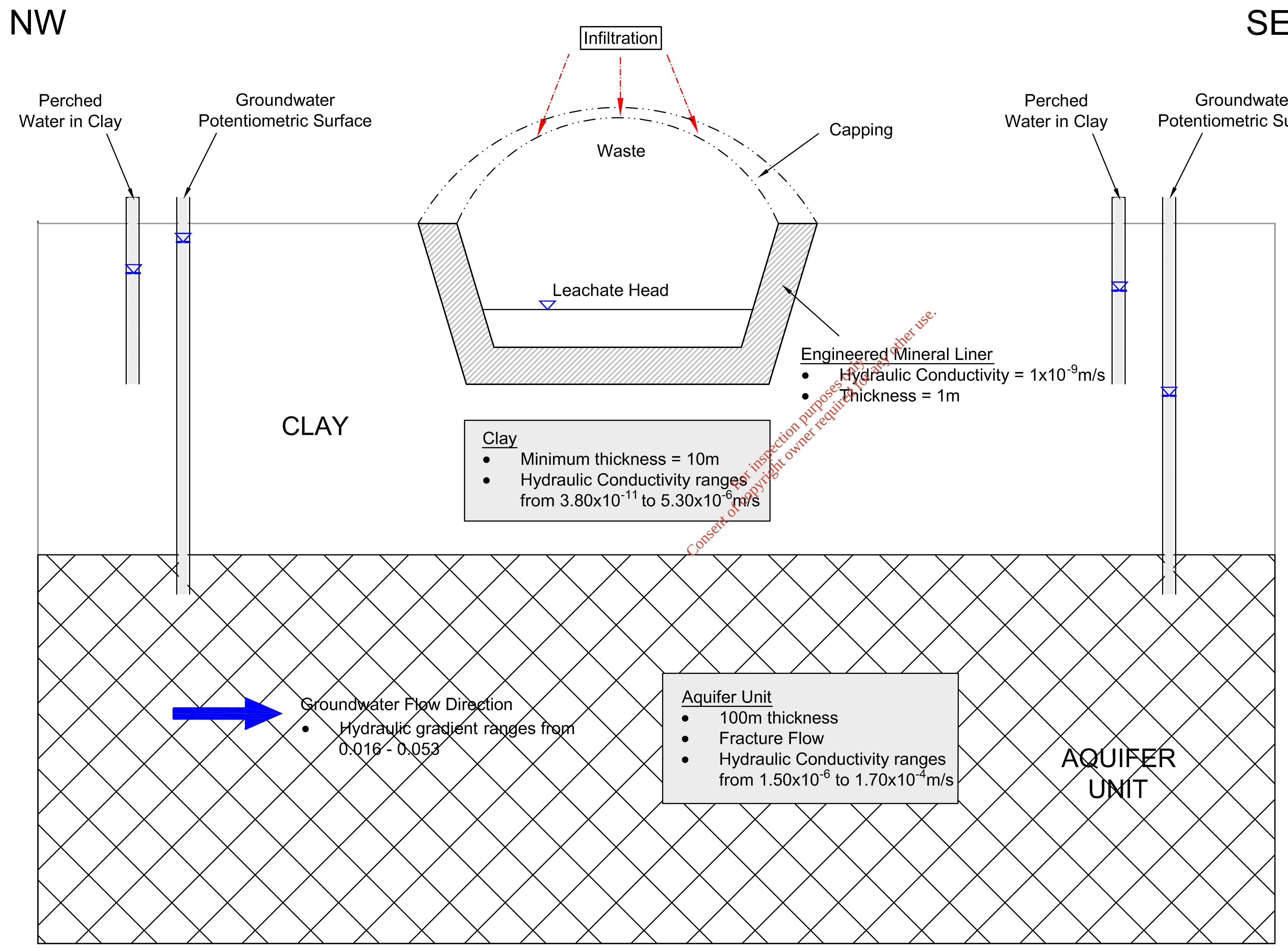
Table 5.2: Literature Data

Data	Literature Source	Role within model
Waste characteristics	EPA Landfill Site Design Manual	Used to determine the rate at which water infiltrates through the waste
Biodegradation rates	LandSim manual, ConSim manual and data from Review of Ammonium attenuation in soil and groundwater (Ref 2)	Used to define the rate at which contaminants biodegrade as they travel through clay subsoils and bedrock aquifer.
Retardation rates	LandSim and ConSim manual	Used to define the rate at which contaminants are retarded with respect to groundwater movement as they travel through the engineered mineral liner, clay subsoils and bedrock aquifer
Pathway porosity of clay (subsoil) and bedrock aquifer	Data ranges provided in Domenico and Schwartz (Ref 3)	Used to define the rate at which contaminants can travel through the clay (subsoil) and the bedrock aquifer

Because the model software supports a probabilistic analysis the input parameters can be entered as ranges within the model with distributions that reflect variability and uncertainty. The input parameters used in the model are presented in **Appendix A** and the approach to selecting input parameters for various aspects of the model is discussed in the following sections.

The physical characteristics of the main components of the hydrogeological system are presented as a conceptual cross section in **Figure 7**.

Conceptual Site Model



Notes

Rev:	Date:	Amendment:	Name:	Checked:
-	-	-	-	-

Drawing Based Upon: -

Status: Preliminary

Notes: Contractors are not to scale from this drawing. All dimensions to be checked on site and any discrepancies, ambiguities and/or omissions between this drawing and information given elsewhere must be reported to this office. If in doubt, ask.

RPS
Conrad House Beaufort Square Chepstow Monmouthshire NP16 5EP
T 01291 621821 F 01291 627827 E rpssw@rpsgroup.com W www.rpsgroup.com

Client: -

Project: Fingal Landfill EIS

Title: General Conceptual Model for the site

Date: 29.01.09 Scale: NTS Original Paper Size: A3

Drawn: RC Checked: LW /RG Job Ref: JER4201

Figure Number: 007 Rev: -

www.rpsgroup.com

Drawing Ref:JER4201-006_29.01.09_General Conceptual Model for the site

5.2.2 Water Balance and Infiltration

Leachate head is accounted for both during the operational lifetime of the site and at a hypothetical time when leachate management controls have ceased. For the hypothetical unmanaged scenario the variation of the leachate head is internally calculated within the model to allow the advective flow to be calculated.

Rainfall data has been obtained from the meteorological station at Dublin Airport; the data comprises average monthly precipitation data from 1980 to 2005 **Appendix B**.

The model will make an allowance for climate change impacts by the application of a 10% increase in rainfall volume over and above the current average annual rainfall. The average annual precipitation at Dublin Airport is 783.5mm/year; this value will be increased by 10% (to 861.9mm/year) as the input to the model.

Leachate levels within the landfill are dependant on the water balance for the site. A conservative water balance has been constructed, taking into consideration the following assumptions:

- Open waste areas are subject to direct infiltration from rainfall comprising annual average precipitation (861.9mm/year) as recommended by guidance. It is assumed that all rainfall that falls on the open waste areas infiltrates into it and that no evaporation occurs (Ref.6).
- The value of infiltration once the final cap has been emplaced is 58.4mm/year; this is obtained by calculating the amount of surface runoff and potential evapotranspiration that will occur
- No absorptive capacity of waste has been accounted for as recommended by guidance due to waste moisture release on decomposition and compaction.
- Leachate levels controlled during managed period (minimum of 60 years from start of land filling) and then allowed to recover assuming an unmanaged landfill.
- Leachate recirculation accounted for during active landfilling to aid waste decomposition and contaminant source term flushing.

The decline in leachate concentrations is strongly controlled by water inputs to the waste mass as described above. The total water inputs in waste are based on the infiltration pre and post capping.

5.2.3 Leachate Source Term Characteristics

5.2.3.1 Waste Types

The types of waste to be received at the landfill for disposal include:

- Non-hazardous Municipal Waste;
- Industrial Non-Hazardous Waste;
- Construction and Demolition Waste;

- Biological sludge produced as a waste by-product of the on site leachate treatment system;
- Residues from Water and Wastewater Treatment; and
- Bottom Ash from Non-hazardous Waste to Energy Plants.

Hazardous waste other than the normal hazardous component which constitutes less than 1% of household waste will not be accepted at the facility

The landfill will be capable of accepting 500,000 tonnes of waste annually for the first 3-5 years and thereafter an annual tonnage of 300,000. This means that the landfill will have a filling lifetime of up to 30 years.

5.2.3.2 Leachate Quality

In order to determine the source term for the risk assessment, potential leachate quality for the site has been characterised using a variety of sources. Four sources have been used to provide data on leachate quality concentrations for different types of landfills. The data sources include:

- Composition of acetogenic leachate samples from large landfills with a relatively dry high waste input rate (UK Department of the Environment [1995]);
- Composition of methanogenic leachate samples from large landfills in the UK with a relatively dry high waste input rate (UK Department of the Environment [1995]);
- Characterisation table of acetogenic leachate sampled from eight landfills across Ireland (MSc Thesis [2005]); and
- Default leachate composition from the LandSim manual, data is compiled from many domestic waste sites within the UK.

The data obtained from the four different sources is tabulated in **Appendix C**.

Determinands used within the model to represent contaminants within the leachate were selected using the following process

1. The information sources above were used to identify maximum concentrations in leachate for all listed determinands;
2. The determinands were divided into the following groups according to their physico-chemical properties and toxicity: inorganic cations, inorganic anions, hydrophilic organic chemicals, hydrophobic organic chemicals, List I metals and List II metals;
3. The maximum concentrations for each determinant were compared to published guideline values. For List I substances the maximum value was screened against its Minimum Reporting Value (MRV) as given in the EA guidance on Hydrogeological Risk Assessment for Landfills. For List II substances the maximum value has then been screened against the lower of Irish Drinking Water Standard (DWS) or the Environmental Quality Standard (EQS) for surface water. In the absence of these standards the World Health Organisation (WHO) health standard was utilised.

4. For each of the groups listed in step 2, determinands that recorded the greatest ratio of screening value to leachate concentration were used to represent leachate within the model.

Chloride and potassium have has also been modelled as a representative conservative anion and cation, respectively, present in leachate. These determinands will represent the migration of a contaminant which is not subject to attenuation processes. Naphthalene has been included to represent petroleum hydrocarbons.

The selected chemical species are shown in Table 5.3 together with the reason for their inclusion and the concentration range assigned within the risk assessment. The minimum and most likely concentration value for each determinant was chosen using the highest value from the range of data sources.

Table 5.3: Leachate Source Term Concentrations

Leachate Species	Reason for inclusion	Concentration Range (mg/l)			Source of data
		Min	Likely	Max	
List I					
Cadmium	Heavy metal (low mobility ion)	0.00003	0.01	0.105	See Appendix C
Mercury	Heavy metal (low mobility ion)	0.00004	0.00009	0.00195	See Appendix C
Naphthalene	Hydrophobic organic compound	0.001	0.01	0.1	Conservative estimates based on professional judgement
List II					
Ammonium	Inorganic cation	0.895	451.3	3590.5	See Appendix C
Nickel	Heavy metal (metallic ion)	0.0302	0.133	1.87	See Appendix C
Phenol	Organic hydrophilic	0.001	0.01	0.1	Conservative estimates based on professional judgement
Other					
Iron	Heavy metal (metallic ion)	0	15.3	59796	See Appendix C
Chloride	Inorganic anion	9	1243.5	9850	See Appendix C
Potassium	Inorganic cation	2.4	604.15	3100	See Appendix C

As there are no data sources for either phenol or naphthalene the values set within LandSim are conservative estimates based on professional judgement.

5.2.3.3 Source Term Decline

The change in leachate concentration of non-volatile species over time will be controlled by how rapidly the waste mass is flushed by infiltration and by how readily any non-volatile species are released from the solid to the aqueous phase. The rate of release from the solid to liquid phase is defined by the kappa value (LandSim v2.5). Default kappa values are presented in LandSim; these values are based on analysis of an extensive data set of existing kappa values (Golder Associates, 2003) which have indicated a strong relationship between kappa and initial leachate concentration. The kappa values used in the assessment are presented in **Appendix A**.

The change in concentration of volatile organic compounds (VOCs) will be strongly controlled by removal via landfill gas extraction.

5.2.4 Contaminant Pathways

5.2.4.1 Overview

The conceptual model has identified four media components to sub-surface contaminant pathways beneath the landfill that will be subject to various transport mechanisms and attenuation processes. The processes considered within the numerical model are summarised in Table 5.4 and discussed in more detail below

Table 5.4: Summary of Pathway Media and Processes

Pathway Media	Contaminant Transport Mechanisms	Attenuation Processes
HDPE Liner	Direct Leakage through damage or defects or as result of degradation of liner	Declining source term. Dilution of leachate by rainwater infiltrating waste. Degradation of contaminants within leachate
Mineral Liner (vertical pathway)	Advection or Diffusion	Retardation
Clay subsoil (vertical pathway)	Advection or Diffusion	Retardation, Dispersion, Degradation
Aquifer unit (Horizontal pathway/saturated zone)	Advection	Dilution, Retardation, Dispersion, Degradation

Each of the elements presented in the table is discussed separately below.

Both advection and diffusion are possible contaminant migration mechanisms throughout the lifecycle of the landfill. The dominant mechanism depends on the relationship between leachate levels and external hydraulic heads within the in-situ clay subsoils and the underlying aquifer unit. As a conservative simplification both mechanisms have been modelled separately for the entire lifecycle of the site up to 20,000 years. This will reflect the worst outcomes of both mechanisms in isolation, independent of which migration mechanism is dominating at a specific place or time within the landfill during the modelled lifetime of the site.

5.2.4.2 Direct Leakage through HDPE Liner

The LandSim default values defining defects in the membrane liner following installation under a Construction Quality Assurance (CQA) scheme have been adopted. Six stages in the lifecycle of a membrane liner in terms of the generation of defects is accounted for within LandSim;

- Liner construction;
- During landfilling;

- A period after landfilling during which no defects are generated;
- Liner degradation due to oxidation;
- Further stress cracking during oxidation; and
- Continuing deterioration.

The detect values used within the advection model are given in **A**.

5.2.4.3 Advective Transport

Advective transport is driven by difference in hydraulic heads between different strata and has been modelled using the Landsim Model. Advective transport is described by Darcy's Law and is influenced by the hydraulic conductivity of the media through which transport occurs i.e. the engineered mineral liner, the in-situ clay or the aquifer unit and the difference in groundwater and leachate levels within the different model components.

5.2.4.4 Diffusive Transport

Diffusive transport, described by Fick's Law has been modelled using the EA spreadsheet for contaminant fluxes in hydraulically contained landfills.

To model diffusive flux the worst case scenario has been chosen, this is where hydraulic containment is most limited and leachate head within the landfill is approaching the elevation of the perched water level in the clay. Under such conditions the rate of diffusion will be at it's greatest. This scenario has been modelled for the lifetime of the site over 20,000 years.

The EA Spreadsheet does not allow for a declining source term and therefore diffusive contaminant fluxes are based on a finite source term which is a conservative assumption.

5.2.4.5 Vertical Pathway

For the advective transport model the vertical pathway comprises 10m of low permeability in-situ clay subsoils beneath the landfill footprint. The engineered mineral liner is modelled as a separate entity within LandSim.

Within the diffusion model the vertical pathway within the model comprises the 1 m of engineered mineral liner and 10 m of low permeability in-situ clay subsoils beneath the landfill footprint and has been considered as a single unit within the risk modelling process.

The physical characteristics of the clay subsoils have been defined from site specific data where available (Table 5.1). The permeability of the engineered mineral liner is within the range of values for the in-situ clay. The pathway porosity is modelled as a range from 0.01 to 0.2; this is based on data from Domenico and Schwartz for a clay matrix (*Ref. 3*).

The model input parameters for the vertical pathway are presented in **Appendix A**.

5.2.4.6 Saturated Zone

The saturated zone and horizontal pathway comprises the aquifer unit (sand and gravel and limestone bedrock)

In the absence of any significant intergranular porosity, groundwater flow within the bedrock will occur in fractures and discontinuities that dissect the rock mass. Observations made during the site investigation indicated the rock mass to be completely shattered in places and therefore the weathered zone would act as an equivalent porous medium. For the purpose of the modelling the aquifer unit is considered to have a total saturated thickness of 100 m however, the mixing depth in which dilution of infiltrating leachate will occur is limited to 10 m.

The permeability of fractured bedrock has been derived from site specific data on transmissivities within the bedrock and sands and gravels (Table 5.1).

A porosity range of between 0.01 and 0.24 (Ref. 3) has been assigned to the aquifer unit to account for the likely presence of areas of negligible fracturing and more developed secondary porosity along jointing of faulting within the bedrock. This range of values is representative of the effective porosity for a limestone aquifer matrix and is considered to be representative of the aquifer unit beneath the site.

The model input parameters for the saturated zone are presented in **Appendix A.**

5.2.4.7 Dilution

Both during and following management of the site, leachate will be diluted by infiltrating rainfall. Leachate migrating through the clay subsoils will be subject to dilution upon reaching the aquifer unit.

5.2.4.8 Retardation

Retardation processes will occur in the mineral liner component of the composite liner whereby organics and metals may be subject to sorption processes including adsorption, chemisorption, absorption and ion exchange.

These processes serve to slow or retard the movement of dissolved phase contaminants relative to groundwater movement. These processes do not result in mass removal of the contaminants.

Cation exchange processes will occur in the liner but this is not included as an attenuation process in the software used for the assessment. This is considered a conservative approach to the assessment.

The retardation factor is defined as the ratio between the rate of movement of the contaminant and the rate of movement of groundwater and is influenced by the soil-water partition coefficient (Kd)

Given the highly variable range of retardation values in the hydrogeological literature a number of sources have been consulted to determine the range of soil-water partition coefficient (Kd) values. **Appendix D** details the minimum, maximum and most likely values of Kd for the selected contaminants.

For organic contaminants the Kd is a product of the organic carbon partition coefficient (Koc) and the fraction of organic carbon within the soil. Organic carbon partition coefficient (Koc) values were adopted from the ConSim manual. The fraction of organic carbon has been determined from five samples taken from the site from both the clay subsoils and limestone bedrock.

5.2.4.9 Dispersion

Dispersion describes the spreading of a contaminant plume within a porous media due to the arrangement of mineral grains. Dispersion can occur both along the direction of the flowpath (longitudinal dispersion) and normal to the flowpath (transverse dispersion).

Dispersion is only accounted for within the LandSim model and not represented in the diffusion model. The magnitude of dispersivity is proportional to pathway length (L) and for short pathway lengths (up to 100m) can be represented by simple empirical relationship whereby longitudinal dispersivity (in the direction of groundwater flow) is defined as 10% of the pathway length (Pickens and Grisak, 1981). It is recommended that the value of transverse dispersivity should be around 3% of the pathway length.

Within the LandSim model longitudinal dispersivity is modelled in the vertical pathway and the aquifer unit. Transverse dispersivity is modelled only within the aquifer unit.

5.2.4.10 Degradation within Pathway Media

Degradation processes result in mass removal of contaminants. Metallic and inorganic contaminants are unlikely to be subject to degradation processes. Degradation of organic contaminants can occur via biotic or abiotic reactions depending upon the contaminant. For the organic contaminants considered within this assessment (naphthalene and phenol) the most likely method of degradation is via oxidation-reduction reactions, catalysed by micro-organisms with the organic contaminant as the electron donor. These reactions generally occur most readily under aerobic conditions however they can also occur under anaerobic conditions although the rate of degradation is likely to be less. Conditions within the mineral liner and clay subsoil beneath the landfill are likely to be anerobic and therefore half lives for contaminants within the in-situ-clay and the aquifer unit have been based on anaerobic conditions. The half-lives used within the model are presented within **Appendix A**.

5.2.5 Compliance Points

The following compliance points have been defined within the risk model to be protective of the identified receptors:

1. The base of the vertical pathway prior to dilution – (List I substances);

2. Groundwater within aquifer unit 100m down hydraulic gradient of the peoposed waste footprint – (List II substances, chloride and potassium).

The compliance point within the aquifer unit is based on a monitoring borehole located within the application boundary 100 m directly down gradient (southeast) of the landfill footprint (ER12). The nearest groundwater user (Thomas Kerrigan) is located approximately 800 m to the south of the proposed landfill and is located across gradient rather than directly down gradient, therefore, adopting a compliance point 100 m directly down gradient of the proposed footprint is a conservative assumption which will be protective of users of groundwater within the aquifer unit.

Table 5.5 shows the Guideline Concentrations for the priority contaminants which have been used as assessment criteria at the compliance points, in the assessment;

Table 5.5: Guideline Concentrations for Priority Contaminants at Compliance Point

Contaminant	Guideline Concentration* (mg/l)	
	*1	*2
Ammonium		0.3
Chloride		250
Iron		0.2
Potassium		12
Phenol		0.0005
Nickel		0.02
Cadmium (List 1)	0.001	
Naphthalene (List 1)	0.001	
Mercury (List 1)	0.0001	

*1 - Minimum Reporting Values (MRV) after EA Fact Sheet, Issue April 2008, Groundwater Trigger Levels, Minimum Reporting Values and limits of detection (List I substances)

*2 – Irish Drinking Water Standards (DWS) or Environmental Quality Standard (EQS) whichever is the lowest. (Ref. 5)

5.3 SUMMARY OF ASSUMPTIONS

In order to represent the site within the risk assessment model a number of simplifying assumptions have been made. Where generalizing assumptions have been made they err on the side of conservatism. The principal simplifying assumptions and their effect on the Risk Assessment model are described in Table 5.6.

Table 5.6: Risk Assumption Model

Assumption	Reality	Effect on Model
1m head across entire landfill	Head will vary due to sloping base of cell. Entire area will not be in operation at any one time	Over predicts the amount of leachate generated
No HDPE liner in the diffusion transport model	There is an HDPE liner	The concentration of contaminants at the compliance point is over predicted
No declining source term for diffusion transport model. i.e. the leachate concentration remains constant.	Concentrations in leachate will decline through degradation and dilution by infiltrating rainwater	The concentration of contaminants at the compliance point is over predicted
A 10m thickness of in-situ clay has been modelled for both transport scenarios	In some areas across the proposed area of the site the thickness of the clay will be greater	Over predicts the concentration of contaminants at the compliance point as there will be a greater thickness of the clay in which

Assumption	Reality	Effect on Model
		contaminants can be retarded and are subject to biodegradation
Maximum possible diffusive flow rate modelled where landfill leachate is approaching the elevation of perched water in clay	Diffusion fluxes will be lower due to the presence of advective inward flow due to hydraulic containment	Model will over calculate the migration of contaminants to the aquifer unit via the vertical pathway and the concentration at the compliance point will be over predicted
The landfill is considered as a single phase with waste deposited over the entire landfill footprint during the operational phase	The site will be managed in 11 phases of landfilling progressively capped over the operational phase limiting the generation of leachate	The maximum concentration of contaminants within leachate will migrate through the entire footprint of the site simultaneously rather than being limited by phasing. This results in an over prediction of leachate migrating from the site and is therefore conservative

5.4 UNCERTAINTY AND SENSITIVITY ANALYSIS

Uncertainty within the selection of input parameters is addressed by the use of a probabilistic approach to the risk modelling. As the input parameters are entered as ranges then so to are the results returned as ranges and defined according to the probability of occurrence. The 95th percentile represents a 95% confidence level that the actual value will be less than that predicted in the model. In the case of predicted contaminant concentrations the 95th percentile represents a 95% probability that the predicted contaminant concentration at the compliance point will be lower than predicted. The 95th percentile values are used as outputs from the model, which are representative of the reasonable worst-case performance of the landfill (Ref.4). Because the assessment uses a probabilistic approach a sensitivity analysis is not required.

5.5 HYDROGEOLOGICAL COMPLETION CRITERIA

Completion relating to hydrogeological risks will have been achieved when there are no further risks of pollution from the landfill, i.e. when the site can comply with the requirements of the Groundwater Directive, without the need for any active management.

The model undertaken represents the entire lifecycle of the site, including defects in, and degradation of, the lining system, and the predicted leachate quality and levels in the site following the cessation of management controls.

6 RESULTS OF RISK ASSESSMENT

6.1 INTRODUCTION

The models predict the concentrations of the priority contaminants at both the List I and List II compliance points as appropriate (Section 5.2.5). The compliance point for List I substances is at the base of the vertical pathway. The compliance point for List II substances is 100m downgradient of the edge of the waste within the application boundary. The 95th percentile (worst case) concentrations are reported for each of the modelled scenarios and have been compared to the Guideline Concentrations. The guideline concentrations at the compliance point are as presented in Section 5.2.5.

The results for the advective and diffusive transport scenarios are presented separately below. For each of the modelled transport scenarios the predicted concentration of each determinant is expressed as a percentage of the guideline concentration (Table 5.5). Where no breakthrough occurs no percentage has been calculated.

Breakthrough has been defined as concentrations of contaminants greater than 1 x10^{-9} mg/l, which is based on 0.001% of the minimum MRV reported in Table 5.5.

6.2 ADVECTIVE TRANSPORT

Results for the advective transport scenario are presented in Tables 6.1 to 6.2 and are reported at:

- 30 years after the start of landfilling which represents the anticipated operational lifetime of the site (Table 6.1);
- 60 years from start of landfilling which represents the earliest anticipated time at which management controls could theoretically cease subject to the requirements of the waste licence (Table 6.2); and
- the time at which the peak concentration occurs during the 20,000 years of the modelled lifetime of the site (Table 6.3).

Table 6.1: Concentrations of Determinands During the Operational Phase – at 30 Years (End of Landfilling)

Determinant	Predicted 95th percentile concentrations after 30 years (mg/l)		Predicted concentration as % of guideline concentration	
	At base of vertical pathway (List 1)	100m from edge of waste (List II)	At base of vertical pathway (List I)	100m from edge of waste (List II)
Ammonium		No breakthrough		No breakthrough
Nickel		No breakthrough		No breakthrough
Phenol		No breakthrough		No breakthrough
Iron		No breakthrough		No breakthrough
Chloride		13.2		5.28%

Determinant	Predicted 95th percentile concentrations after 30 years (mg/l)		Predicted concentration as % of guideline concentration	
Potassium		0.027		0.225%
Cadmium	No breakthrough		No breakthrough	
Naphthalene	No breakthrough		No breakthrough	
Mercury	No breakthrough		No breakthrough	

Table 6.2: Concentrations of Determinands at the End of Management – 60 Years After the Start of Filling

Determinant	Predicted 95th percentile concentrations after 60 years (mg/l)		Predicted concentration as % of guideline concentration	
	At base of vertical pathway (List 1)	**100m from edge of waste (List II)**	**At base of vertical pathway (List 1)**	**100m from edge of waste (List II)**
Ammonium		No breakthrough		
Nickel		No breakthrough		
Phenol		No breakthrough		
Iron		No breakthrough		
Chloride		10.1		4.04%
Potassium		0.003		0.025%
Cadmium	No breakthrough		No breakthrough	
Naphthalene	No breakthrough		No breakthrough	
Mercury	No breakthrough		No breakthrough	

The results indicate that assuming an advective transport scenario across the whole of the site for a period of 20,000 years, no breakthrough of List I substances will occur during the anticipated managed lifetime of the site (60 years from start of filling).

Chloride and potassium are the only determinants to record predicted breakthrough at the List II compliance point within the managed lifetime of the site (60 years from the start of landfilling). Chloride and potassium are conservative ions which do not undergo retardation or degradation and therefore represent a worst case with respect to mobility. Chloride and potassium are not List I or List II contaminants under the groundwater directive but have been included as they are abundant within leachate and are the most conservative with respect to mobility.

Predicted concentrations of chloride and potassium show a slight decrease at 60 years after start of land filling when compared to the end of the operational phase (30 years) which reflects the emplacement of the cap and the declining source term. As the composite liner system, in particular the HDPE liner, degrades the amount of contaminants released will gradually increase to reach the maximum predicted concentrations in Table 6.3.

Table 6.3: Peak Concentrations of Determinands Throughout the Entire Landfill Lifetime

Determinand	Predicted Peak Concentrations, C, (mg/l) at time, t, during 20,000 years				Predicted concentration as % of guideline concentration	
	At base of vertical pathway (List 1)		100m from edge of waste (List II)		At base of vertical pathway (List 1)	100m from edge of waste (List II)
	C (mg/l)	T (years)	C (mg/l)	t (years)		
Ammonium			5.02×10^{-8}	520		0.0000167%
Iron			4.70×10^{-7}	20,000		0.000235%
Nickel			1.67×10^{-3}	20,000		8.35%
Phenol			No breakthrough			
Chloride			165	300		66%
Potassium			0.104	14		0.86%
Cadmium	1.14×10^{-5}	20,000			1.14%	
Naphthalene	No breakthrough					
Mercury	No breakthrough					

*Peak concentrations based on 95th percentile

The only List I substance to record breakthrough within the modelled lifetime of the site of 20,000 years is cadmium, which will take greater than 20,000 years to reach a maximum concentration. The maximum predicted concentration of cadmium, achieved after 20,000 years is only 1.14% of its guideline value which is based on the minimum reporting value (MRV) and indicates that it not be detectable with current laboratory methods. Cadmium concentrations will therefore not cause any discernible change in groundwater quality.

None of the List II substances record peak concentrations greater than 10% of their respective guidelines within the modelled lifetime of the site of 20,00 years. None of these contaminants will have a discernible impact upon groundwater quality within the aquifer unit.

Chloride, which is not a List I or List II substance, is the only determinant which may be recorded at detectable concentrations at the List II compliance point 100 m down gradient of the proposed waste footprint (ER12), during the managed lifetime of the site. The predicted concentrations do not exceed guideline concentrations. The predicted concentrations of Chloride with respect to background concentrations are discussed in section 6.4.

6.3 DIFFUSSIVE TRANSPORT

Table 6.4 shows the predicted concentrations for the diffusive flux scenario. The table shows the breakthrough times expressed as years after start of land filling, for contaminants and the maximum (95th percentile) predicted concentrations at 20,000 years. If the breakthrough time is shown as greater than 20,000 years then the maximum concentration has not been reached. The diffusive transport scenario does not take account of a declining source term and so the predicted concentrations will be over predicted and consequently the breakthrough times (time taken to reach a concentration of greater than 1×10^{-9} mg/l) will be underestimated.

Table 6.4: Predicted Concentrations for the Diffusive Flux Scenario

Determinant	Breakthrough Time (	Predicted Max Concentrations (mg/l)		Predicted concentration as % of guideline concentration	
	Years (after start of land filling)	List I Base of vertical pathway (MRV List I)	List II Aquifer 100m down-gradient	At base of vertical pathway (List 1)	100m from edge of waste within aquifer (List II)
Ammonium	3,000		$6.4x10^{-3}$		2%
Iron	>20,000		No breakthrough		
Nickel	>20,000		No breakthrough		
Phenol	1,600		$4.5x10^{-7}$		0.09%
Chloride	250		0.11		0.044%
Potassium	100		0.039		0.325%
Cadmium	No breakthrough	No breakthrough			
Naphthalene	No breakthrough	No breakthrough			
Mercury	No breakthrough	No breakthrough			

The results for the diffusive transport pathway show that for the List I substances breakthrough at the compliance point does not occur within the modelled lifetime of the site of 20,000 years.

None of the List II substances record breakthrough at the List II compliance point within the theoretical managed lifetime of the site (60 years after start of land filling). Chloride and potassium record the shortest breakthrough times as they are conservative contaminants which will not be subject to retardation. None of the maximum (95^{th} percentile) predicted concentrations exceed 2% of their respective guideline concentrations over the modelled lifetime of the site of 20,000 years and will have no discernible impact on groundwater quality within the aquifer unit.

6.4 BACKGROUND CONCENTRATIONS

Considering both the advective and diffusive flux scenarios, the peak concentration of chloride (based on the 95^{th} percentile) is 165mg/l (at 300 years) during the lifetime of the landfill at the List II compliance point. This concentration will be in addition to the background concentrations of chloride which range between 30mg/l and 70mg/l. Considering the highest background concentration, chloride will still not exceed the guideline concentration of 250mg/l after 300 years. During the managed lifetime of the site, the predicted concentration of chloride is below the lowest observed background concentration of 30 mg/l.

Chloride is not a List II substance and therefore not required to be controlled under the Groundwater Regulations. It must be noted that this standard is a guide value and is not health-related, but set to avoid taste and corrosion potential in potable water supplies. It should also be noted that the predicted concentrations of choride are based on the conservative assumptions made in the risk models.

Background concentrations of cadmium down gradient of the foot print range from <0.4ug/l to 3.8ug/l. The maximum concentration of cadmium observed is 0.0114ug/l after 20,000 years. Elevated concentrations of Nickel up gradient and down gradient of the footprint have been recorded. Concentrations range from 1-100ug/l down-gradient of the footprint. The maximum concentration observed from the LandSim model is 1.67ug/l after 20,000 years. The values obtained from the model for cadmium and nickel are considerably smaller than the background concentrations measured on site.

None of the other determinants of concern have been detected downgradient of the proposed landfill footprint.

6.5 SUMMARY OF RESULTS

- For both the advective and diffusive scenarios no breakthrough of List I or List II substances are predicted during the theoretical managed lifetime of the site i.e. within 60 years of the start of landfilling;.

- Cadmium is the only List I substance to record breakthrough at the compliance point within the modelled lifetime of the site of 20,000 years. The predicted 95th percentile concentration of 1.14×10^{-5} mg/l, is not detectable with current laboratory methods and is only 1.14% of the minimum reporting value of 0.001 mg/l.

- None of the List II substances record peak concentrations greater than 10% of their respective guidelines within the modelled lifetime of the site of 20,00 years for either an advective of diffusive transport scenario. The predicted concentrations are sufficiently low that none of these contaminants will have a discernible impact upon groundwater quality within the aquifer unit.

- Chloride is the only determinant which may record detectable concentrations down-gradient of the landfill during the theoretical managed lifetime of the site. The predicted concentrations are below guideline and background concentrations and will not present a risk to groundwater.

7 COMPLIANCE WITH LEGISTLATION

7.1 COMPLIANCE WITH THE LANDFILL DIRECTIVE

Leachate Collection. Due to the likely presence of List I and II substances in leachate, the landfill has been engineered to include a leachate drainage and collection system as required by the Landfill Directive (1999) for non-hazardous landfills. There is a requirement to collect leachate generated from the landfill.

7.2 COMPLIANCE WITH THE GROUNDWATER DIRECTIVE

1. Groundwater Regulations. The Protection of Groundwater Regulations (S.I 41 of 1999) apply to the site due to the non-hazardous classification of the waste deposited at the site and the likely presence of List I and II substances in the landfill leachate, which could potentially discharge to groundwater.

2. Prior Investigation. Previous investigations at the site have been used to develop the conceptual understanding of the hydrogeological system, which has formed the basis of the risk assessment.

3. Entry of List I and List II substances to groundwater. The engineering of the proposed landfill has been engineered with the aim of preventing the discharge of List I substances and pollution by List II substances. A groundwater risk assessment has been undertaken to confirm whether the design has met these requirements.

The results of the risk assessments show that List I substances in leachate are prevented from discharging directly to groundwater beneath the site.

The results of the risk assessment for List II substances in leachate have shown that the landfill design prevents pollution of groundwater beneath the site from these substances.

1. Essential and technical precautions. Technical precautions have been outlined for the site, including leachate control measures, construction and maintenance of a low permeability cap and lining system;

2. Requisite Surveillance. Requisite surveillance in the form of risk based leachate and groundwater monitoring will be undertaken at the site, as part of an Environmental Monitoring Plan. This will ensure that any impact from the landfill will be detected and remedial action taken before any significant impact to groundwater can occur.

8 CONCLUSIONS

The proposed Fingal Landfill development will comprise a new fully engineered landfill at a greenfield site. The proposed landfill will comprise an excavated void within the low permeability clay subsoils lined with a composite liner system comprising engineered clay and an overlying HDPE membrane. A minimum of 10 metres vertical thickness of low permeability clay subsoils will be preserved beneath the proposed landfill footprint. .

Priority contaminants have been identified within leachate based on published literature values for concentrations within landfill leachate and the degree of elevation above their respective groundwater quality compliance criteria. Both List I and List II substances have been modelled to assess performance at two defined compliance points – at the base of the vertical pathway representing both the engineered mineral liner and in situ clay subsoils for List 1 substances and at a lateral distance of 100 metres down gradient of the waste footprint within the aquifer unit for List II Substances.

Contaminant migration mechanisms within the landfill will depend on the distribution of groundwater heads across the site - both within the in situ clay subsoils and the underlying aquifer unit - and the relative elevation of leachate within the site - both during the operational phase and the post management lifetime. Where groundwater elevations exceed landfill leachate elevations, the site will be hydraulically contained by an inward hydraulic gradient. Under such a scenario, advection out of the site is prevented and only diffusion may occur along the concentration gradient that exists from high concentrations within the leachate and low concentrations below the site within the vertical pathway. Where leachate head exceeds groundwater heads, typically following the cessation of management controls when leachate is allowed to recover, advection out of the site will occur from the landfill into the vertical pathway.

Both these transport mechanisms, diffusion and advection, have been assessed by this risk assessment. In order to identify worst case outcomes, both processes have been modelled using conservatively chosen input parameters from the commencement of tipping for duration of 20,000 years, identified by the Environment Agency (England and Wales) as representing the maximum effective lifetime for a landfill.

The models have predicted that:

- at the 95th percentile (reasonable worst case) none of the priority contaminants are predicted to exceed guideline concentrations at their respective List I or List II compliance point over the modelled lifetime of the site of 20,000 years;

- All of the List I and List II contaminants have been predicted at such low concentrations below typical laboratory detection limits that it can be concluded that there will be no discernible impact on groundwater quality at the receptor over the modelled lifetime of the site of 20,000 years;

- Chloride is the only determinant which may record detectable concentrations down-gradient of the landfill during the theoretical managed lifetime of the site. The predicted concentrations are below guideline and background concentrations and will not present a risk to groundwater.

In conclusion, the detailed, conservative and probabilistic risk assessments have shown that the proposed engineered landfill, situated within a low environmental risk setting within low permeability clay subsoils, will not result in deterioration in groundwater quality in the aquifer unit beneath the site. The proposed Landfill does not, therefore present a risk to groundwater and does not contravene the requirements of the Groundwater Directive.

9 REFERENCES

Ref 1 Environment Agency (England and Wales), Contaminant fluxes from hydraulic containment landfills: a review. Science Report SC0310/SR, 2004

Ref 2 Review of Ammonium attenuation in soil and groundwater, National Groundwater and Contaminated Land Centre, NGWCLC Report NC/02/49, 2003

Ref 3 Domenico, P. A. and Schwartz, F.W., Physical and Chemical Hydrogeology, 1990

Ref 4 Environment Agency (England and Wales). Hydrogeological Risk Assessments for Landfills, 2003

Ref 5 Environmental Protection Agency, Towards Setting Guideline Values for the Protection of Groundwater in Ireland, 2001

Ref 6 Environmental Protection Agency, Landfill Manuals, 2000

APPENDIX A

INPUT PARAMETERS FOR THE MODELS

APPENDIX A: INPUT PARAMETERS FOR THE MODELS

A.1 ENGINEERING PARAMETERS

Cell Dimensions	Unit	Distribution Type*	Range			Justification
			Minimum value	Expected value	Maximum value	
Cell Base Area	ha	Single value		2.12		Calculated by LandSim
Cell Top Area	ha	Single value		2.5		Calculated by LandSim
Number of Cells	-	Single value		23		Specified value
Total base area	ha	Single value		48.8		Calculated by LandSim
Total top area	ha	Single value		57.5		Top area of landfill
Final Waste Thickness	m	Triangular	12	19	33	Thickness of waste depends on the location within the site, at a minimum it will be 12m up to a maximum of 33m
Head of leachate when surface water breakout occurs	m	Single value		12		Minimum thickness of waste
Waste porosity	fraction	Uniform	0.40		0.60	EPA Landfill Site Design Manual
Waste Dry Density	kg/l	Uniform	0.75		1	
Waste Field Capacity	fraction	Uniform	0.20		0.35	

Head on composite liner system	m	Single value		1		Leachate head will be maintained at 1m above the base of the landfill during the management period
Properties of composite Liner System						
Hydraulic conductivity of engineered mineral liner	m/s	Single value		$1x10^{-9}$		Specified value
Design thickness of engineered mineral liner	m	Single value		1		1m of engineered barrier
Pathway moisture content	fraction	Log Uniform	0.073		0.246	Optimum calculated moisture content for the clay
Pathway longitudinal dispersivity	m	Single value		0.1		0.1 x pathway length
Onset of flexible membrane liner (FML) degradation	Years since filling commenced	Single value		150		LandSim Default
Time for area of defects to double	Years	Single value		100		LandSim Default
Membrane Defects (number per hectare)						
Pin holes	-	Uniform	0		25	Default for fair liner quality
Holes	-	Uniform	0		5	
Tears	-	Triangular	0	0.1	2	

*Describes statistical distribution used in model to represent input parameters

A.2 INFILTRATION TO OPEN WASTE

Infiltration information	Unit	Distribution Type*	Range			Justification
			Minimum value	Expected value	Maximum value	
Cap design infiltration	mm/year	Single Value		58.4		Estimated infiltration through clay cap plus 10%
Infiltration to open waste	mm/year	Single value		861.9		Total rainfall measured at Dublin airport weather station plus 10%
Time Offset	Years	Single value		0		No offset
End of filling	Years from start of waste deposit	Single value		30		Proposed duration of filling
Duration of Management Period	Years from start of waste deposit	Single value		60		Minimum anticipated management period set at 30 years after cessation of filling

*Describes statistical distribution used in model to represent input parameters

A.3 SOURCE CONCENTRATIONS FOR ADVECTIVE AND DIFFUSIVE MODELLING

Contaminant	Unit	Distribution Type*	Range			Justification
			Minimum value	Expected value	Maximum value	
Ammonium	mg/l	Log Triangular	0.895	451.35	3590.5	Appendix A
Chloride	mg/l	Log Triangular	9	1243.5	9850	Appendix A
Cadmium	mg/l	Log Triangular	$3x10^{-5}$	0.01	0.105	Appendix A
Mercury	mg/l	Log Triangular	$4x10^{-5}$	$9x10^{-5}$	0.00195	Appendix A
Nickel	mg/l	Log Triangular	0.0302	0.133,	1.87	Appendix A
Iron	mg/l	Log Triangular	$1x10^{-30}$	15.3,	59796	Appendix A
Potassium	mg/l	Log Triangular	2.4,	604.15	3100	Appendix A
Phenol	mg/l	Log Triangular	0.001	0.01	0.1	Conservative values
Naphthalene	mg/l	Log Triangular	0.001	0.01	0.1	Conservative values
Treated Leachate Recirculated	m^3/hr	Uniform	2.08		4.17	Based on estimates of leachate recirculation of 50-100 m^3/day

*Describes statistical distribution used in model to represent input parameters

A.4 DECLINING SOURCE TERM PARAMETERS FOR ADVECTIVE MODELLING

Decline in Contaminant Concentration in Leachate	Unit	Distribution Type*	Range					Justification
			Minimum value	Expected value			Maximum value	
Kappa Values				**$t_{1/2}$**	***c***	***m***		
Ammonium	kg/l	Single Value		-	0.59	0		LandSim default Kappa values
Chloride	kg/l	Single Value		-	0.2919	0.0298		
Cadmium	kg/l	Single Value		-	0.1589	0.0823		
Potassium	kg/l	Single Value		-	5.9774	2.0188		
Mercury	kg/l	Single Value		-	0.1643	0.0767		
Iron	kg/l	Single Value		-	0.1246	2.9837		
Nickel	kg/l	Single Value		-	-0.1479	0.0987		
Source Half Life								
Naphthalene	years	Single value		10				LandSim default for where gas extraction is taking place
Phenol	years	Single value		10				

*Describes statistical distribution used in model to represent input parameters

A.5 PATHWAY PROPERTIES FOR ADVECTIVE MODELLING

Engineered Mineral Liner Pathway Properties

Retardation parameters	Unit	Distribution Name	Range			Justification
			Minimum value	Expected value	Maximum value	
Ammonium Kd	l/kg	Single value		3.2		ConSim manual for glacial till deposits
Chloride Kd	l/kg	Single value		0		No retardation
Nickel Kd	l/kg	Single value		85.7		Minimum ConSim suggested value
Potassium Kd	l/kg	Single value		0		LandSim suggested value
Iron Kd	l/kg	Log Uniform	1		40,000	LandSim suggested range
Mercury Kd	l/kg	Single value		3,835.4		Suggested value from ConSim manual for glacial till deposits
Cadmium Kd	l/kg	Single value		222.2		Minimum ConSim suggested value for glacial till deposits
Naphthalene: Koc	ml/g	Single value		1,288		ConSim Suggested Input Parameters
Phenols: Koc	ml/g	Single value		27		ConSim Suggested Input Parameters
Fraction of Organic Carbon	fraction	Log Uniform	0.003		0.010	Analysis of clay samples from site

*Describes statistical distribution used in model to represent input parameters

Vertical Pathway Properties

Vertical pathway dimensions	Unit	Distribution Type*	Range			Justification
			Minimum value	Expected value	Maximum value	
Pathway length	m	Single value		10		Minimum of 10m of clay subsoils beneath the landfill and above the aquifer
Pathway porosity	Fraction	Log Uniform	0.01		0.2	Effective porosity for clay matrix (Ref. 3)
Hydraulic Conductivity	m/s	Log Triangular	$3.8x10^{-11}$	$8.19x10^{-10}$	$5.3x10^{-6}$	Measured from in-situ tests on the clay subsoils
Longitudinal dispersivity	m	Single value		1		Longitudinal dispersivity = 0.1 x pathway length
Retardation parameters						
Ammonium Kd	l/kg	Single value		3.2		ConSim manual for glacial till deposits
Chloride Kd	l/kg	Single value		0		No retardation
Nickel Kd	l/kg	Single value		85.7		Minimum ConSim suggested value
Potassium Kd	l/kg	Single value		0		LandSim suggested value
Iron Kd	l/kg	Log Uniform	1		40,000	LandSim suggested range
Mercury Kd	l/kg	Single value		3,835.4		Suggested value from ConSim manual for glacial till deposits
Cadmium Kd	l/kg	Single value		222.2		Minimum ConSim suggested value for glacial till deposits
Naphthalene: Koc	ml/g	Single value		1288		ConSim Suggested Input Parameters
Phenols: Koc	ml/g	Single value		27		ConSim Suggested Input Parameters
Fraction of Organic Carbon	fraction	Log Uniform	0.003		0.01	Analysis of clay samples from site
Pathway density	kg/l	Uniform	1.8		2.2	Dry bulk density for clay matrix (Ref.3)
Contaminant Half-lives						
Ammonium	years	Uniform	5		10	Ref. 2
Chloride	years	Single value		$1x10^{9}$		LandSim default values (no degradation)
Cadmium	years	Single value		$1x10^{9}$		
Potassium	years	Single value		$1x10^{9}$		
Mercury	years	Single value		$1x10^{9}$		
Iron	years	Single value		$1x10^{9}$		
Nickel	years	Single value		$1x10^{9}$		
Naphthalene	years	Uniform	2.1		2.3	Naphthalene and Phenol half lives taken from the ConSim user manual suggested input parameters for an anaerobic pathway
Phenol	years	Uniform	0.14		0.82	

Aquifer Pathway Properties

Aquifer Pathway dimensions	Units	Distribution Type*	Range			Justification
			Minimum value	Expected value	Maximum value	
Pathway regional gradient	-	Log triangular	0.016	0.032	0.053	Raw data
Pathway hydraulic conductivity	m/s	Log triangular	$1.5x10^{-6}$	$1.5x10^{-4}$	$1.7x10^{-4}$	Raw data
Pathway porosity	Fraction	Log Uniform	0.01		0.24	Effective porosity for aquifer matrix (Ref. 3)
Pathway length	m	Single Value		500		Calculated by LandSim
Pathway width	m	Single value		1,200		Maximum width of landfill
Mixing Zone	m	Single value		10		10% of total saturated thickness of bedrock aquifer
Longitudinal Dispersivity	m	Single value		120		0.1 x pathway length
Transverse Dispersivity	m	Single value		39.6		0.33x longitudinal dispersivity
Retardation parameters						
Ammonium Kd	l/kg	Log Uniform	0.5		2	Minimum LandSim suggested value
Chloride Kd	l/kg	Single Value		0		LandSim suggested value
Nickel Kd	l/kg	Log Uniform	20		800	Minimum LandSim suggested value
Cadmium Kd	l/kg	Log Uniform	1.6		1,500	Minimum LandSim suggested value
Iron Kd	l/kg	Log Uniform	1		40,000	Minimum LandSim suggested
Mercury Kd	l/kg	Log Uniform	450		3,835	Minimum LandSim suggested value
Potassium Kd	l/kg	Single Value		0		LandSim suggested value

Naphthalene Koc	ml/g	Single Value		1,288		ConSim suggested input parameters
Phenol Koc	ml/g	Single Value		27		ConSim suggested input parameters
Fraction of organic carbon	Fraction	Log Uniform	0.002		0.015	Measured from 2 samples of gravel/bedrock
Pathway density	kg/l	Uniform	1.74		2.79	Dry bulk density for limestone matrix (Ref.3)
Contaminant Half-lives						
Ammonium	years	Uniform	5		10	Ref. 2
Chloride	years	Single value		$1x10^9$		LandSim default values (no degradation)
Cadmium	years	Single value		$1x10^9$		
Potassium	years	Single value		$1x10^9$		
Mercury	years	Single value		$1x10^9$		
Iron	years	Single value		$1x10^9$		
Nickel	years	Single value		$1x10^9$		
Naphthalene	years	Uniform	2.1		2.3	Naphthalene and Phenol half lives taken from the ConSim user manual suggested input parameters for an anaerobic pathway
Phenol	years	Uniform	0.14		0.82	

*Describes statistical distribution used in model to represent input parameters

Diffusion Model Parameters comments will be similar to above. Format needs sorting

	Unit	Distribution Type*	Range			Justification
			Minimum value	Expected value	Maximum value	
Landfill Construction						
Basal width perpendicular to groundwater flow	m	Single value		462		Width based on proposed footprint dimensions
Basal length parallel to groundwater flow	m	Single value		1,060		Length based on proposed footprint dimensions
Elevation of base of landfill	mAOD	Single value		41		Proposed basal elevation
Elevation of top of aquifer	mAOD	Single value		30		Modelled aquifer top, below the base of the landfill is 1m of engineered mineral liner and 10m of in-situ clay/clay subsoils
Leachate head inside landfill	mAOD	Single value		44.99		Worst case scenario for diffusive flux
Groundwater head outside landfill	mAOD	Single value		45		Worst case scenario for diffusive flux
Free water diffusion coefficient, D_w						
Ammonium	m^2/s	Single value		$1.96x10^{-9}$		*Contaminant fluxes from hydraulic containment landfills*
Chloride	m^2/s	Single value		$2.03x10^{-9}$		
Cadmium	m^2/s	Single value		$7.17x10^{-10}$		
Potassium	m^2/s	Single value		$1.96x10^{-9}$		
Naphthalene	m^2/s	Single value		$6.45x10^{-10}$		
Phenol	m^2/s	Single value		$1x10^{-9}$		No data available so default constant D_w utilised (Ref. Appelo, C.A.J. and Postma, D., Geochemistry, groundwater and pollution, 2nd Edition, 2005)
Nickel	m^2/s	Single value		$1x10^{-9}$		
Mercury	m^2/s	Single value		$1x10^{-9}$		
Iron	m^2/s	Single value		$1x10^{-9}$		
Retardation Parameters						

Ammonium	l/kg	Uniform	0.5		2	LandSim suggested values
Chloride	l/kg	Single		0		LandSim suggested value
Cadmium	l/kg	Log Triangular	1.6		1500	LandSim suggested values
Potassium	l/kg	Single		0		LandSim suggested value
Phenol	l/kg	Log Uniform	0.054		0.405	Based on site foc data and ConSim suggested Kd input parameter
Naphthalene	l/kg	Uniform	2.576		19.32	Based on site foc data and ConSim suggested Kd input parameter
Nickel	l/kg	Log uniform	20		800	LandSim suggested values
Mercury	l/kg	Log uniform	450		3,835	LandSim suggested values
Iron	l/kg	Log uniform	1		40,000	LandSim suggested values
Mineral Barrier/Liner						
Thickness of mineral liner	m	Single value		11		Thickness of in-situ clay/ clay subsoil (10m) and engineered mineral liner (1m)
Hydraulic conductivity	m/s	Log Triangular	$3.8x10^{-11}$	$8.19x10^{-10}$	$5.3x10^{-6}$	Measured from in-situ tests on the clay subsoils
Average pore radius	m	Single value		$7x10^{-7}$		*Contaminant fluxes from hydraulic containment landfills*
Effective porosity	-	Log uniform	0.01		0.2	Effective porosity for clay matrix (Ref. 3)
Dry bulk density	kg/m^3	Uniform	1,800		2,200	Dry bulk density for clay matrix (Ref.3)
Tortuosity	-	Uniform	2		10	*Contaminant fluxes from hydraulic containment landfills*
Steady State Dilution (List II)						
Hydraulic gradient in the aquifer	-	Log Triangular	0.016	0.032	0.053	Raw data
Hydraulic conductivity of the aquifer	m/s	Log triangular	$1.5x10^{-6}$	$1.5x10^{-4}$	$1.7x10^{-4}$	Raw data
Down gradient distance of compliance point from landfill	m	Single		100		List II compliance point down gradient of the site within the proposed license area

*Describes statistical distribution used in model to represent input parameters

APPENDIX B

PRECIPITATION DATA

APPENDIX B: PRECIPITATION DATA

Precipitation figures taken from meteorological station at Dublin Airport; averages are over 1980-2005

Dublin Airport (1980-2005)	
Month	**Mean Rainfall (mm)**
January	69.3
February	53.4
March	54.5
April	58.2
May	60.5
June	69.3
July	50.5
August	72.5
September	60.5
October	86.1
November	73.2
December	75.5
Annual Total	**783.5**

APPENDIX C

LEACHATE SOURCE TERM DATA

APPENDIX C: LEACHATE SOURCE TERM DATA

C.1 LITERATURE DATA FOR LEACHATE CONCENTRATIONS

The following four tables show the data that has been utilised in compiling the maximum, minimum and most likely values for the source term

Table C1.1 Composition of acetogenic leachates sampled from large landfills with a relatively dry high waste input rate (EPA Landfill Manuals - Landfill Site Design [2000])

Determinant	Units	Minimum	Maximum	Median	Mean
Ammoniacal N	mg/l	194	3610	582	922
Arsenic (As)	mg/l	<0.001	0.148	0.01	0.024
Cadmium (Cd)	mg/l	<0.01	0.1	0.01	0.02
Calcium (Ca)	mg/l	270	6240	1600	2241
Chloride (Cl)	mg/l	659	4670	1490	1805
Chromium (Cr)	mg/l	0.03	0.3	0.12	0.13
Copper (Cu)	mg/l	0.02	1.1	0.075	0.13
Fatty acids (as C)	mg/l	963	22414	5144	8197
Iron (Fe)	mg/l	48.3	2300	475	653.8
Lead (Pb)	mg/l	<0.04	0.65	0.3	0.28
Magnesium (Mg)	mg/l	25	820	400	384
Manganese (Mn)	mg/l	1.4	164	22.95	32.94
Mercury (Hg)	mg/l	<0.0001	0.0015	0.0003	0.0004
Nickel (Ni)	mg/l	<0.03	1.87	0.23	0.42
Nitrate (as N)	mg/l	<0.2	18	0.7	1.8
Nitrite (as N)	mg/l	0.01	1.4	0.1	0.2
PH	value	5.12	7.8	6	6.73
Phosphate (as P)	mg/l	0.6	22.6	3.3	5
Potassium (K)	mg/l	350	3100	900	1143
Sodium (Na)	mg/l	474	2400	1270	1371
Sulphate (SO_4)	mg/l	<5	1560	608	678
TOC	mg/l	1010	29000	7800	12217
Zinc (Zn)	mg/l	0.09	140	6.85	17.37

Table C1.2 Summary of composition of methanogenic leachates sampled from large landfills with a relatively dry high waste input rate (EPA Landfill Manuals - Landfill Site Design [2000])

Determinant	Units	Minimum	Maximum	Median	Mean
Alkalinity (as $CaCO_3$)	mg/l	3000	9130	5000	5376
Ammoniacal N	mg/l	283	2040	902	889
Arsenic (As)	mg/l	<0.001	0.485	0.009	0.034
Cadmium (Cd)	mg/l	<0.01	0.08	<0.01	0.015
Calcium (Ca)	mg/l	23	501	117	151
Chloride (Cl)	mg/l	570	4710	1950	2074
Chromium (Cr)	mg/l	<0.03	0.56	0.07	0.09
Copper (Cu)	mg/l	<0.02	0.62	0.07	0.13
Fatty acids (as C)	mg/l	<5	146	5	18
Iron (Fe)	mg/l	1.6	160	15.3	27.4
Lead (Pb)	mg/l	<0.04	1.9	0.13	0.2
Magnesium (Mg)	mg/l	40	1580	166	250
Manganese (Mn)	mg/l	0.04	3.59	0.3	0.46
Mercury (Hg)	mg/l	<0.0001	0.0008	<0.0001	0.0002
Nickel (Ni)	mg/l	<0.03	0.6	0.14	0.17
Nitrate (as N)	mg/l	0.2	2.1	0.7	0.86
Nitrite (as N)	mg/l	<0.01	1.3	0.09	0.17
pH	value	6.8	8.2	7.35	7.52
Phosphate (as P)	mg/l	0.3	18.4	2.7	4.3
Potassium (K)	mg/l	100	1580	791	854
Sodium (Na)	mg/l	474	3650	1400	1480
Sulphate (SO_4)	mg/l	<5	322	35	67
TOC	mg/l	184	2270	555	733
Zinc (Zn)	mg/l	0.03	6.7	0.78	1.14

Table C1.3 Characterisation table of acetogenic leachate sampled from eight landfills across Ireland (MSc Thesis [2005])

Determinant	Units	Minimum	Maximum	Median	Mean
Ammoniacal N	mg/l	0.9	2539	325.6	551
Argon (Ar)	ug/l	4.06	5	5	4.687
Arsenic (As)	ug/l	1	1	1	1
Barium (Ba)	mg/l	0.106	0.3	0.21	0.2053
Beryllium (Be)	ug/l	1	1	1	1
Boron (B)	ug/l	0	1270	50	249
Cadmium (Cd)	ug/l	0.03	0.1	0.1	0.086
Calcium (Ca)	mg/l	117	237	187	180
Chloride	mg/l	9	9850	820	1487
Chromium (Cr)	ug/l	0.05	10	7	6.04
Copper (Cu)	mg/l	0.0028	0.17	0.065	0.0757
Cyanide (CN)	mg/l	0.01	10	1	2.6
Iron (Fe)	mg/l	0	59796	13	4541
Lead (Pb)	ug/l	0.001	0.2	0.1	0.1003
Magnesium (Mg)	mg/l	1	92.3	1	26.7
Manganese (Mn)	mg/l	0.7	7.4	4.05	4.05

Molybdenum (Mo)	ug/l	1	7	5	4.5
Mercury (Hg)	ug/l	0.05	0.1	0.05	0.0667
Nickel (Ni)	mg/l	0.0302	0.1	0.061	0.0637
Nitrate (as N)	mg/l	0.001	0.269	0.01	0.0435
Ortho Phosphate (as P)	mg/l	0.03	29.5	0.65	5.33
PH	value	5.8	8.2	7.285	7.2136
Total Phosphate (as P)	mg/l	0.367	2.9	0.808	1.211
Potassium (K)	mg/l	2.4	1130.5	417.3	484
Selenium (Se)	ug/l	2.5	10.4	5	5.57
Silver (Ag)	ug/l	10	50	30	30
Sodium (Na)	mg/l	0	2388	547	809
Sulphate (SO4)	mg/l	0.25	0.25	0.25	0.25
Thalium (Tl)	ug/l	1	1	1	1
Thorium (Th)	ug/l	0.9	1.8	1	1.175
Tin (Sn)	mg/l	6	7	6	6.333
TON	mg/l	0.03	25.2	0.795	3.947
Uranium (U)	mg/l	10	330	270	220
Vanadium (V)	ug/l	4.34	4.34	4.34	4.34
Zinc (Zn)	mg/l	0.0488	0.09	0.0694	0.0694

Table C1.4 Summary of default leachate inventory - from LandSim manual

Determinant	Units	Minimum	Maximum	Median
Ammoniacal N	mg/l	32.1	1100	267
Arsenic (As)	mg/l	0.00371	0.0107	0.00485
Cadmium (Cd)	mg/l	0.0019	0.105	0.0101
Chloride (Cl)	mg/l	227	2650	997
Chromium (Cr)	mg/l	0.0231	0.416	0.0981
Copper (Cu)	mg/l	0.0129	0.191	0.0509
Lead (Pb)	mg/l	0.0337	0.34	0.111
Mercury (Hg)	mg/l	0.00004	0.00195	0.00009
Nickel (Ni)	mg/l	0.0345	0.627	0.126
Nitrite (as N)	mg/l	0.01	6.01	0.27
Phosphate	mg/l	0.01	22.6	2.54
Potassium (K)	mg/l	40.8	1140	321
Zinc (Zn)	mg/l	0.0296	9	0.362

C.2 MAXIMUM CONCENTRATIONS IN SOURCE TERM

	Guideline concentration	units	Maximum value	units	Max value>standard?	No times over standard	Reference for max value
Inorganic anion							
Ortho Phosphate (as P)	0.03	mg/l	29.5	mg/l	Yes	983	3
Chloride	250	mg/l	9850	mg/l	Yes	39	3
Cyanide (CN)	0.05	mg/l	10	mg/l	Yes	200	3
Sulphate (SO4)	200	mg/l	1560	mg/l	Yes	8	1
Nitrite (as N)	0.1	mg/l	6.01	mg/l	Yes	60	4
Nitrate (as N)	50	mg/l	18	mg/l	No	0	1
Inorganic cation							
Ammonium (NH4)	0.3	mg/l	3590.5	mg/l	Yes	11,968	1
Ammonia (NH3)	0.02	mg/l	19.5	mg/l	Yes	975	
Potassium (K)	12	mg/l	3100	mg/l	Yes	258	1
Magnesium (Mg)	50	mg/l	1580	mg/l	Yes	32	2
Calcium (Ca)	200	mg/l	6240	mg/l	Yes	31	1
Sodium (Na)	150	mg/l	3650	mg/l	Yes	24	2
Heavy metal (List I)							
Mercury (Hg)	0.0001	mg/l	0.00195	mg/l	Yes	20	4
Cadmium (Cd)	0.001	mg/l	0.105	mg/l	Yes	105	4
Heavy metal (List II)							
Iron (Fe)	0.2	mg/l	59796	mg/l	Yes	298,980	3
Manganese (Mn)	0.05	mg/l	164	mg/l	Yes	3,280	1
Nickel (Ni)	0.02	mg/l	1.87	mg/l	Yes	94	1
Silver (Ag)	0.05	ug/l	50	ug/l	Yes	1,000	3
Tin (Sn)	25	ug/l	7000	ug/l	Yes	280	3
Lead (Pb)	0.01	mg/l	1.9	mg/l	Yes	190	2

Arsenic (As)	0.01	mg/l	0.485	mg/l	Yes	49	1
Zinc (Zn)	5	mg/l	140	mg/l	Yes	28	1
Chromium (Cr)	0.05	mg/l	0.56	mg/l	Yes	11	2
Copper (Cu)	2	mg/l	1.1	mg/l	No	1	1
Boron (B)	1	mg/l	1.27	mg/l	Yes	1	1
Selenium (Se)	10	ug/l	10.4	ug/l	Yes	1	1
Molybdenum (Mo)	70	ug/l	7	ug/l	No	0	1
Vanadium (V)	20	ug/l	4.34	ug/l	No	0	1
Barium (Ba)	0.1	mg/l	0.3	mg/l	Yes	3	1
Hydrophilic organic							
Phenols	0.0005	mg/l					
Hydrophobic organic							
Naphthalene	0.001	mg/l					

Reference Sources:

1. Summary table (A1.1) for the composition of acetogenic leachates sampled from large landfills with a relatively dry high waste input rate (EPA Landfill Manuals - Landfill Site Design [2000])
2. Summary table (A1.2) for the composition of methanogenic leachates sampled from large landfillls with a relatively dry high waste input rate (EPA Landfill Manuals - Landfill Site Design [2000])
3. Characterisation table (A1.3) of acetogenic leachate sampled from eight landfills across Ireland (MSc Thesis [2005])
4. Summary table (A1.4) of default leachate inventory from LandSim manual

Blank cells indicate that no data is available

C.3 MINIMUM CONCENTRATIONS IN SOURCE TERM

	Minimum value	unit	Ref for minimum value
Inorganic anion			
Chloride	9	mg/l	3
Ortho Phosphate (as P)	0.03	mg/l	3
Cyanide (CN)	0.01	mg/l	3
Sulphate (SO4)	0.25	mg/l	3
Nitrite (as N)	0.01	mg/l	1,4
Nitrate (as N)	0.001	mg/l	3
Inorganic cation			
Ammonium (NH4)	0.895	mg/l	3
Ammonia (NH3)	0.0049	mg/l	3
Potassium (K)	2.4	mg/l	3
Magnesium (Mg)	1	mg/l	3
Calcium (Ca)	23	mg/l	2
Sodium (Na)	0	mg/l	3
Heavy metal (List I)			
Mercury (Hg)	0.00004	mg/l	4
Cadmium (Cd)	0.00003	mg/l	3
Heavy metal (List II)			
Iron (Fe)	0	mg/l	3
Manganese (Mn)	0.04	mg/l	2
Nickel (Ni)	0.0302	mg/l	3
Tin (Sn)	6000	ug/l	3
Lead (Pb)	0.000001	mg/l	3
Arsenic (As)	0.001	mg/l	3
Zinc (Zn)	0.0296	mg/l	4
Chromium (Cr)	0.00005	mg/l	3
Silver (Ag)	10	ug/l	3
Copper (Cu)	0.0028	mg/l	3
Boron (B)	0	mg/l	3
Selenium (Se)	2.5	ug/l	3
Molybdenum (Mo)	1	ug/l	3
Vanadium (V)	4.34	ug/l	3
Barium (Ba)	0.106	mg/l	3
Hydrophilic organic			
Phenols		mg/l	
Hydrophobic organic			
Naphthalene		mg/l	

C.4 MEDIAN VALUES IN SOURCE TERM

	Median value	Unit
Inorganic anion		
Chloride	1243.5	mg/l
Ortho Phosphate (as P)	0.65	mg/l
Cyanide (CN)	1	mg/l
Sulphate (SO4)	35	mg/l
Nitrite (as N)	0.1	mg/l
Nitrate (as N)	0.7	mg/l
Inorganic cation		
Ammonium (NH4)	451.30	mg/l
Ammonia (NH3)	2.45	mg/l
Potassium (K)	604.15	mg/l
Magnesium (Mg)	166	mg/l
Calcium (Ca)	187	mg/l
Sodium (Na)	1270	mg/l
Heavy metal (List I)		
Mercury (Hg)	0.00009	mg/l
Cadmium (Cd)	0.01	mg/l
Heavy metal (List II)		
Iron (Fe)	15.3	mg/l
Manganese (Mn)	4.05	mg/l
Nickel (Ni)	0.133	mg/l
Tin (Sn)	6000	ug/l
Lead (Pb)	0.1205	mg/l
Arsenic (As)	0.006925	mg/l
Zinc (Zn)	0.571	mg/l
Chromium (Cr)	0.08405	mg/l
Silver (Ag)	30	ug/l
Copper (Cu)	0.0675	mg/l
Boron (B)	0.05	mg/l
Selenium (Se)	5	ug/l
Molybdenum (Mo)	5	ug/l
Vanadium (V)	4.34	ug/l
Barium (Ba)	0.21	mg/l
Hydrophilic organic		
Phenols		mg/l
Hydrophobic organic		
Naphthalene		mg/l

APPENDIX D

LITERATURE VALUES OF PARTITION COEFFICIENTS

APPENDIX D: LITERATURE VALUES OF PARTITION COEFFICIENTS

The following tables show data from literature sources for the soil-water partition coefficient (Kd) values.

Data in Table D1 is from the LandSim manual where values are based on partition coefficients in sand and loam.

Table C1 Kd values from LandSim manual

Species	Kd (l/kg)	
	Minimum	**Maximum**
Ammoniacal N	0.5	2
Cadmium	1.6	1,500
Chloride	0	0
Iron	1	40,000
Mercury	450	3,835
Nickel	20	800
Potassium	0	0

Data in Table D2 is from the ConSim manual. Differing Kd values are presented for the determinands based on the type of material.

Table D2 Inorganic Kd values from ConSim manual

Determinand	Kd	Units	Type of material
Ammonium	3.2	ml/g	glacial till, unspecified pH
	0.5-2	ml/g	loam, unspecified pH
Cadmium	222.2	ml/g	glacial till, unspecified pH
	minimum=1.6, expected=40, maximum=990	ml/g	loam, unspecified pH
Chloride	0	ml/g	
Iron	minimum=200, expected=810, maximum=3,300	ml/g	loam, unspecified pH
Mercury	3,835.4	ml/g	glacial till, unspecified pH
	1,500	ml/g	loam, unspecified pH
Nickel	85.7	ml/g	glacial till, unspecified conditions
	300	ml/g	loam, unspecified pH

Data in Table D4 shows the organic carbon partition coefficient (Koc) values for phenol and naphthalene. Data is sourced from the ConSim manual.

Table D3 Organic Koc Data from ConSim manual

Determinand	Koc	units
Phenol	27	ml/g
Naphthalene	1288	ml/g

APPENDIX E1

INPUTS & OUTPUTS FROM LANDSIM MODEL

Calculation Settings

Number of iterations: 201

Results calculated using sampled PDFs

Full Calculation

Clay Liner:

Retarded values used for simulation

No Biodegradation

Unsaturated Pathway:

Retarded values used for simulation

Biodegradation

Saturated Vertical Pathway:

Retarded values used for simulation

Biodegradation

Aquifer Pathway:

Retarded values used for simulation

Biodegradation

Timeslices at: 30, 60, 100, 1000

Decline in Contaminant Concentration in Leachate

Potassium	Non-Volatile
c (kg/l): 5.9774	m (kg/l): 2.0188
Ammonium	Non-Volatile
c (kg/l): 0.59	m (kg/l): 0

Contaminant Half-lives (years)

Unsaturated Pathway:

Cadmium	SINGLE(1e+009)
Chloride	SINGLE(1e+009)
Iron	SINGLE(1e+009)
Mercury	SINGLE(1e+009)
Naphthalene	UNIFORM(2.1,2.3)
Nickel	SINGLE(1e+009)
Phenols	UNIFORM(0.14,0.82)
Potassium	SINGLE(1e+009)
Ammonium	UNIFORM(5,10)

Saturated Vertical Pathway:

Cadmium	SINGLE(1e+009)
Chloride	SINGLE(1e+009)
Iron	SINGLE(1e+009)
Mercury	SINGLE(1e+009)
Naphthalene	UNIFORM(2.1,2.3)
Nickel	SINGLE(1e+009)
Phenols	UNIFORM(0.14,0.82)
Potassium	SINGLE(1e+009)
Ammonium	UNIFORM(5,10)

Aquifer Pathway:

Cadmium	SINGLE(1e+009)
Chloride	SINGLE(1e+009)
Iron	SINGLE(1e+009)
Mercury	SINGLE(1e+009)
Naphthalene	UNIFORM(2.1,2.3)
Nickel	SINGLE(1e+009)
Phenols	UNIFORM(0.14,0.82)
Potassium	SINGLE(1e+009)
Ammonium	UNIFORM(5,10)

Background Concentrations of Contaminants

Justification for Contaminant Properties

All units in milligrams per litre

Phase: Phase 1

Infiltration Information

Cap design infiltration (mm/year):	SINGLE(58.4)
Infiltration to waste (mm/year):	SINGLE(861.9)
End of filling (years from start of waste deposit):	30

Justification for Specified Infiltration

[CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED]

Duration of management control (years from the start of waste disposal): 60

Leachate recirculated AND TREATED (m^3/hr for this phase) UNIFORM(2.08,4.17)

Cell dimensions

Cell width (m):	231
Cell length (m):	92
Cell top area (ha):	2.5
Cell base area (ha):	2.1252
Number of cells:	23
Total base area (ha):	48.8796
Total top area (ha):	57.5
Head of Leachate when surface water breakout occurs (m)	SINGLE(12)
Waste porosity (fraction)	UNIFORM(0.4,0.6)
Final waste thickness (m):	TRIANGULAR(12,19,33)
Field capacity (fraction):	UNIFORM(0.2,0.35)
Waste dry density (kg/l)	UNIFORM(0.75,1)

Justification for Landfill Geometry

[CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED]

Source concentrations of contaminants

All units in milligrams per litre

Declining source term

Cadmium	LOGTRIANGULAR(3e-005,0.01,0.105) *Substance to be treated as List 1*
Chloride	LOGTRIANGULAR(9,1243.5,9850) *Data are spot measurements of Leachate Quality*
Iron	LOGTRIANGULAR(1e-030,15.3,59796) *Data are spot measurements of Leachate Quality*
Mercury	LOGTRIANGULAR(4e-005,9e-005,0.00195) *Substance to be treated as List 1*
Naphthalene	LOGTRIANGULAR(0.001,0.01,0.1) *Substance to be treated as List 1*
Nickel	LOGTRIANGULAR(0.0302,0.133,1.87) *Data are spot measurements of Leachate Quality*
Phenols	LOGTRIANGULAR(0.001,0.01,0.1) *Data are spot measurements of Leachate Quality*
Potassium	LOGTRIANGULAR(2.4,604.15,3100) *Data are spot measurements of Leachate Quality*
Ammonium	LOGTRIANGULAR(0.895,451.3,3590.5) *Data are spot measurements of Leachate Quality*

Justification for Species Concentration in Leachate
[CHANGED]

Drainage Information

Fixed Head.

Head on EBS is given as (m): SINGLE(1)

Justification for Specified Head

Barrier Information

There is a composite barrier

Justification for Engineered Barrier Type

Liner installed under CQA	
Design thickness of clay (m):	SINGLE(1)
Density of clay (kg/l):	SINGLE(1.9)
Pathway moisture content (fraction):	LOGUNIFORM(0.073,0.246)
Onset of FML degradation (years since filling commenced)	150
Pathway longitudinal dispersivity (m):	SINGLE(0.1)
Time for area of defects to double (years)	100

Membrane defects (number per hectare):

Pin holes:	Minimum 0, Maximum 25
Holes:	Minimum 0, Maximum 5
Tears:	Minimum 0, Most Likely 0.1, Maximum 2

The most likely value for the PDFs representing the density of pinholes and holes will move from the minimum value selected above to the maximum value selected above over the time period before FML degradation commences

Justification for Composite: Flexible Membrane Liner
[CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED]

Hydraulic conductivity of mineral lower liner (m/s): SINGLE(1e-009)

Justification for Composite: Clay or BES Substrate Properties
[CHANGED]

Retardation parameters for clay liner

Uncertainty in Kd (l/kg):	
Cadmium	SINGLE(222.2)
Chloride	SINGLE(0)
Iron	LOGUNIFORM(1,40000)
Mercury	SINGLE(3835.4)
Naphthalene: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(1288)
Nickel	SINGLE(85.7)
Phenols: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(27)
Potassium	SINGLE(0)
Ammonium	SINGLE(3.2)
Fraction of Organic Carbon (fraction)	LOGUNIFORM(0.003,0.01)

Justification for Liner Kd Values by Species
[CHANGED] [CHANGED] [CHANGED] [CHANGED]

No unsaturated pathway pathway parameters

Modelled as unsaturated pathway

Pathway length (m):	SINGLE(1e-030)
Flow Model:	porous medium
Pathway moisture content (fraction):	LOGUNIFORM(0.073,0.246)
Pathway Density (kg/l):	UNIFORM(1.8,2.2)

Justification for Unsat Zone Geometry
[CHANGED] [CHANGED]

Pathway hydraulic conductivity values (m/s):	LOGTRIANGULAR(3.8e-011,8.19e-010,5.3e-006)

Justification for Unsat Zone Hydraulics Properties
[CHANGED]

Pathway longitudinal dispersivity (m):	SINGLE(1e-030)

Justification for Unsat Zone Dispersion Properties
[CHANGED]

Retardation parameters for No unsaturated pathway pathway	
Modelled as unsaturated pathway	
Uncertainty in Kd (l/kg):	
Cadmium	SINGLE(222.2)
Chloride	SINGLE(0)
Iron	LOGUNIFORM(1,40000)
Mercury	SINGLE(3835.4)
Naphthalene: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(1288)
Nickel	SINGLE(85.7)
Phenols: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(27)
Potassium	SINGLE(0)
Ammonium	SINGLE(3.2)
Fraction of Organic Carbon (fraction)	LOGUNIFORM(0.003,0.01)

Justification for Kd Values by Species
[CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED]

Aquifer Pathway Dimensions for Phase

Pathway length (m):	UNIFORM(100,600)
Pathway width (m):	SINGLE(1200)

Low permeability soils - clay layer pathway parameters

Modelled as vertical pathway.

Pathway length (m):	SINGLE(10)
Pathway porosity (fraction):	LOGUNIFORM(0.01,0.2)

Justification for Vertical Path Geometry
[CHANGED]

Pathway dispersivity (m): SINGLE(1)

Justification for Vertical Path Dispersion Details
[CHANGED]

Retardation parameters for Low permeability soils - clay layer pathway
Modelled as vertical pathway.
Uncertainty in Kd (l/kg):

Cadmium	SINGLE(222.2)
Retardation parameters for Low permeability soils - clay layer pathway	
Chloride	SINGLE(0)
Retardation parameters for Low permeability soils - clay layer pathway	
Iron	LOGUNIFORM(1,40000)
Retardation parameters for Low permeability soils - clay layer pathway	
Mercury	SINGLE(3835.4)
Retardation parameters for Low permeability soils - clay layer pathway	
Naphthalene: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(1288)
Nickel	SINGLE(85.7)
Naphthalene: Calculated kd	
Phenols: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(27)
Potassium	SINGLE(0)
Phenols: Calculated kd	
Ammonium	SINGLE(3.2)
Phenols: Calculated kd	
Fraction of Organic Carbon (fraction)	LOGUNIFORM(0.003,0.01)

Justification for Vertical Path Kd Values by Species
[CHANGED] [CHANGED] [CHANGED] [CHANGED] [CHANGED]

Pathway Density (kg/l): UNIFORM(1.8,2.2)

Limestone pathway parameters
Modelled as aquifer pathway.

Mixing zone (m): SINGLE(10)

Justification for Aquifer Geometry
[CHANGED]

Pathway regional gradient (-):	TRIANGULAR(0.016,0.032,0.053)
Pathway hydraulic conductivity values (m/s):	LOGTRIANGULAR(1.5e-006,0.00015,0.00017)
Pathway porosity (fraction):	LOGUNIFORM(0.01,0.24)

Justification for Aquifer Hydraulics Properties
[CHANGED]

Pathway longitudinal dispersivity (m):	SINGLE(120)
Pathway transverse dispersivity (m):	SINGLE(39.6)

Justification for Aquifer Dispersion Details
[CHANGED]

Retardation parameters for Limestone pathway

Modelled as aquifer pathway.

Uncertainty in Kd (l/kg):

Cadmium	LOGUNIFORM(1.6,1500)
Chloride	SINGLE(0)
Iron	LOGUNIFORM(1,40000)
Mercury	LOGUNIFORM(450,3835)
Naphthalene: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(1288)
Nickel	LOGUNIFORM(20,800)
Phenols: Calculated kd	
Partition to Organic Carbon ml/g	SINGLE(27)
Potassium	SINGLE(0)
Ammonium	UNIFORM(0.5,2)

Fraction of Organic Carbon (fraction) LOGUNIFORM(0.002,0.015)

Justification for Aquifer Kd Values by Species
[CHANGED] [CHANGED]

Pathway Density (kg/l): UNIFORM(1.74,2.79)

Concentration of Cadmium in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 1.33234E-011
10% of values less than 3.3753E-011
50% of values less than 4.09578E-009
90% of values less than 8.72315E-008
95% of values less than 2.55936E-007

Minimum 2.26678E-016	Maximum 3.05673E-006	
Mean 7.19112E-008	Std. Dev. 3.05145E-007	Variance 9.31134E-014

Concentration of Chloride in groundwater [mg/l]

At 30 years

05% of values less than 0.0398448
10% of values less than 0.0859252
50% of values less than 0.995795
90% of values less than 8.51585
95% of values less than 13.1578
Minimum 0.00255211 Maximum 40.7346
Mean 2.98062 Std. Dev. 5.20737 Variance 27.1167

At 60 years

05% of values less than 0.0692854
10% of values less than 0.113752
50% of values less than 0.854431
90% of values less than 7.17431
95% of values less than 10.1497
Minimum 0.00869053 Maximum 31.0582
Mean 2.43452 Std. Dev. 3.92159 Variance 15.3789

At 100 years

05% of values less than 0.146076
10% of values less than 0.269679
50% of values less than 1.77788
90% of values less than 14.946
95% of values less than 18.4875
Minimum 0.0196158 Maximum 156.578
Mean 5.508 Std. Dev. 12.9646 Variance 168.082

At 1000 years

05% of values less than 0.748937
10% of values less than 1.2476
50% of values less than 6.73149
90% of values less than 36.1689
95% of values less than 62.2585
Minimum 0.10389 Maximum 389.323
Mean 16.9424 Std. Dev. 35.2755 Variance 1244.36

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 5.69929E-009
90% of values less than 4.06762E-007
95% of values less than 1.60588E-006
Minimum 0 Maximum 2.7184E-005
Mean 4.20688E-007 Std. Dev. 2.18585E-006 Variance 4.77795E-012

Concentration of Iron in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 3.83066E-018	
Mean 1.9058E-020	Std. Dev. 2.70494E-019	Variance 7.30047E-038

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 1.70606E-019

Minimum 0	Maximum 3.86581E-007	
Mean 3.7195E-009	Std. Dev. 3.25278E-008	Variance 1.05806E-015

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 4.67649E-008
95% of values less than 4.70216E-007

Minimum 0	Maximum 5.73579E-005	
Mean 6.81706E-007	Std. Dev. 5.11646E-006	Variance 2.61781E-011

Concentration of Mercury in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

Concentration of Naphthalene in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

Concentration of Nickel in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 1.90523E-005
10% of values less than 3.75412E-005
50% of values less than 0.000190062
90% of values less than 0.00123624
95% of values less than 0.00166751

Minimum 4.04532E-007	Maximum 0.00733389	
Mean 0.000464313	Std. Dev. 0.000815754	Variance 6.65455E-007

Concentration of Phenols in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 1.32607E-019
90% of values less than 4.34082E-015
95% of values less than 4.86228E-014

Minimum 0	Maximum 1.60674E-012	
Mean 1.67887E-014	Std. Dev. 1.2084E-013	Variance 1.46022E-026

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 1.34028E-015
95% of values less than 1.56443E-014

Minimum 0	Maximum 5.42328E-013	
Mean 5.54018E-015	Std. Dev. 4.03168E-014	Variance 1.62545E-027

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 2.4338E-016	
Mean 1.38454E-018	Std. Dev. 1.72953E-017	Variance 2.99127E-034

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 2.32877E-018	
Mean 1.15859E-020	Std. Dev. 1.64259E-019	Variance 2.69811E-038

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 2.32878E-018	
Mean 1.1586E-020	Std. Dev. 1.6426E-019	Variance 2.69812E-038

Concentration of Potassium in groundwater [mg/l]

At 30 years

05% of values less than 2.86279E-009
10% of values less than 2.80981E-008
50% of values less than 0.000431828
90% of values less than 0.0202215
95% of values less than 0.0272669

Minimum 2.58973E-012	Maximum 0.0935801	
Mean 0.00583166	Std. Dev. 0.0135325	Variance 0.000183128

At 60 years

05% of values less than 2.20558E-016
10% of values less than 1.35017E-015
50% of values less than 6.2486E-007
90% of values less than 0.00159262
95% of values less than 0.00266923

Minimum 0	Maximum 0.014861	
Mean 0.000495245	Std. Dev. 0.00153994	Variance 2.3714E-006

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 5.2214E-010
90% of values less than 4.41981E-005
95% of values less than 0.000119892

Minimum 0	Maximum 0.000649574	
Mean 2.38132E-005	Std. Dev. 8.75345E-005	Variance 7.66229E-009

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 6.92936E-017
90% of values less than 6.11882E-014
95% of values less than 1.50046E-013

Minimum 0	Maximum 1.72678E-012	
Mean 3.67438E-014	Std. Dev. 1.57317E-013	Variance 2.47488E-026

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 4.08552E-016
90% of values less than 3.5744E-014
95% of values less than 6.61835E-014

Minimum 0	Maximum 5.14585E-013	
Mean 1.41394E-014	Std. Dev. 4.60193E-014	Variance 2.11778E-027

Concentration of Ammonium in groundwater [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 1.15112E-013
10% of values less than 3.93376E-013
50% of values less than 3.29168E-010
90% of values less than 2.17396E-008
95% of values less than 4.28257E-008

Minimum 1.69718E-018	Maximum 1.97468E-007	
Mean 7.42061E-009	Std. Dev. 2.24724E-008	Variance 5.0501E-016

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 9.23568E-011
90% of values less than 1.24743E-008
95% of values less than 3.53991E-008

Minimum 0	Maximum 1.67947E-007	
Mean 5.29532E-009	Std. Dev. 1.7835E-008	Variance 3.18089E-016

Phase: Phase 1

Concentration of Cadmium at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At infinity

05% of values less than 1.59449E-008
10% of values less than 2.72931E-008
50% of values less than 3.70669E-007
90% of values less than 6.10755E-006
95% of values less than 1.14062E-005
Minimum 5.74888E-010 Maximum 4.83978E-005
Mean 2.13673E-006 Std. Dev. 4.83397E-006 Variance 2.33672E-011

Phase: Phase 1

Concentration of Chloride at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 135.363
10% of values less than 212.847
50% of values less than 533.558
90% of values less than 950.471
95% of values less than 1183.12
Minimum 20.9739 | Maximum 1726.71
Mean 572.77 | Std. Dev. 299.208 | Variance 89525.4

At 60 years

05% of values less than 179.827
10% of values less than 217.967
50% of values less than 472.534
90% of values less than 1039.61
95% of values less than 1483.02
Minimum 73.7293 | Maximum 10696.9
Mean 647.62 | Std. Dev. 856.952 | Variance 734367

At 100 years

05% of values less than 240.629
10% of values less than 360.177
50% of values less than 741.906
90% of values less than 1837.81
95% of values less than 2533.17
Minimum 48.3844 | Maximum 4622
Mean 926.559 | Std. Dev. 673.303 | Variance 453337

At 1000 years

05% of values less than 23.0308
10% of values less than 30.8034
50% of values less than 82.8444
90% of values less than 189.472
95% of values less than 235.604
Minimum 5.10703 | Maximum 375.192
Mean 98.5871 | Std. Dev. 66.7737 | Variance 4458.72

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 2.01007E-008
90% of values less than 6.20162E-007
95% of values less than 1.5256E-006
Minimum 0 | Maximum 1.5388E-005
Mean 4.31643E-007 | Std. Dev. 1.78287E-006 | Variance 3.17863E-012

Phase: Phase 1

Concentration of Iron at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 2.54154E-013	
Mean 1.26784E-015	Std. Dev. 1.79265E-014	Variance 3.21359E-028

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 1.70352E-012
95% of values less than 4.87077E-007

Minimum 0	Maximum 3.72296E-005	
Mean 6.42121E-007	Std. Dev. 3.78198E-006	Variance 1.43034E-011

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 5.17885E-007
95% of values less than 5.71177E-006

Minimum 0	Maximum 0.00153564	
Mean 1.64992E-005	Std. Dev. 0.000125021	Variance 1.56302E-008

Phase: Phase 1

Concentration of Mercury at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

Phase: Phase 1

Concentration of Naphthalene at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

Phase: Phase 1

Concentration of Nickel at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0
Minimum 0 Maximum 0
Mean 0 Std. Dev. 0 Variance 0

At infinity

05% of values less than 0.00106809
10% of values less than 0.0014424
50% of values less than 0.00453649
90% of values less than 0.00900866
95% of values less than 0.0109576
Minimum 3.13698E-005 Maximum 0.0212301
Mean 0.00503625 Std. Dev. 0.00320334 Variance 1.02614E-005

Phase: Phase 1

Concentration of Phenols at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 1.03244E-014
90% of values less than 1.44573E-010
95% of values less than 3.2275E-010

Minimum 0	Maximum 1.67679E-008	
Mean 2.52093E-010	Std. Dev. 1.54284E-009	Variance 2.38035E-018

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 2.81568E-015
90% of values less than 3.7932E-011
95% of values less than 1.15164E-010

Minimum 0	Maximum 5.31448E-009	
Mean 7.14306E-011	Std. Dev. 4.51014E-010	Variance 2.03414E-019

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 6.08532E-017

Minimum 0	Maximum 1.62117E-011	
Mean 1.58479E-013	Std. Dev. 1.55494E-012	Variance 2.41785E-024

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

Phase: Phase 1

Concentration of Potassium at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 7.31386E-008
10% of values less than 1.36548E-006
50% of values less than 0.107428
90% of values less than 2.5528
95% of values less than 3.29284
Minimum 5.05926E-010 Maximum 6.26052
Mean 0.80937 Std. Dev. 1.18762 Variance 1.41044

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 1.16436E-005
90% of values less than 0.275815
95% of values less than 0.634352
Minimum 0 Maximum 5.72651
Mean 0.120905 Std. Dev. 0.49359 Variance 0.243632

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 8.13566E-010
90% of values less than 0.00585304
95% of values less than 0.0192197
Minimum 0 Maximum 1.36176
Mean 0.011251 Std. Dev. 0.0991978 Variance 0.00984019

At 1000 years

05% of values less than 0
10% of values less than 0
50% of values less than 1.13824E-016
90% of values less than 7.42181E-013
95% of values less than 1.34453E-012
Minimum 0 Maximum 8.61669E-012
Mean 3.03919E-013 Std. Dev. 1.04137E-012 Variance 1.08446E-024

At infinity

05% of values less than 0
10% of values less than 0
50% of values less than 4.52325E-018
90% of values less than 3.99545E-015
95% of values less than 6.58723E-015
Minimum 0 Maximum 4.73837E-014
Mean 1.60378E-015 Std. Dev. 5.14663E-015 Variance 2.64877E-029

Phase: Phase 1

Concentration of Ammonium at base of Vertical Pathway [mg/l]

At 30 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 60 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 0	
Mean 0	Std. Dev. 0	Variance 0

At 100 years

05% of values less than 0
10% of values less than 0
50% of values less than 0
90% of values less than 0
95% of values less than 0

Minimum 0	Maximum 2.81864E-017	
Mean 1.40231E-019	Std. Dev. 1.98812E-018	Variance 3.95261E-036

At 1000 years

05% of values less than 1.44191E-011
10% of values less than 4.76912E-011
50% of values less than 2.66151E-008
90% of values less than 1.6172E-006
95% of values less than 3.96411E-006

Minimum 2.06351E-013	Maximum 1.38441E-005	
Mean 6.03235E-007	Std. Dev. 1.61435E-006	Variance 2.60614E-012

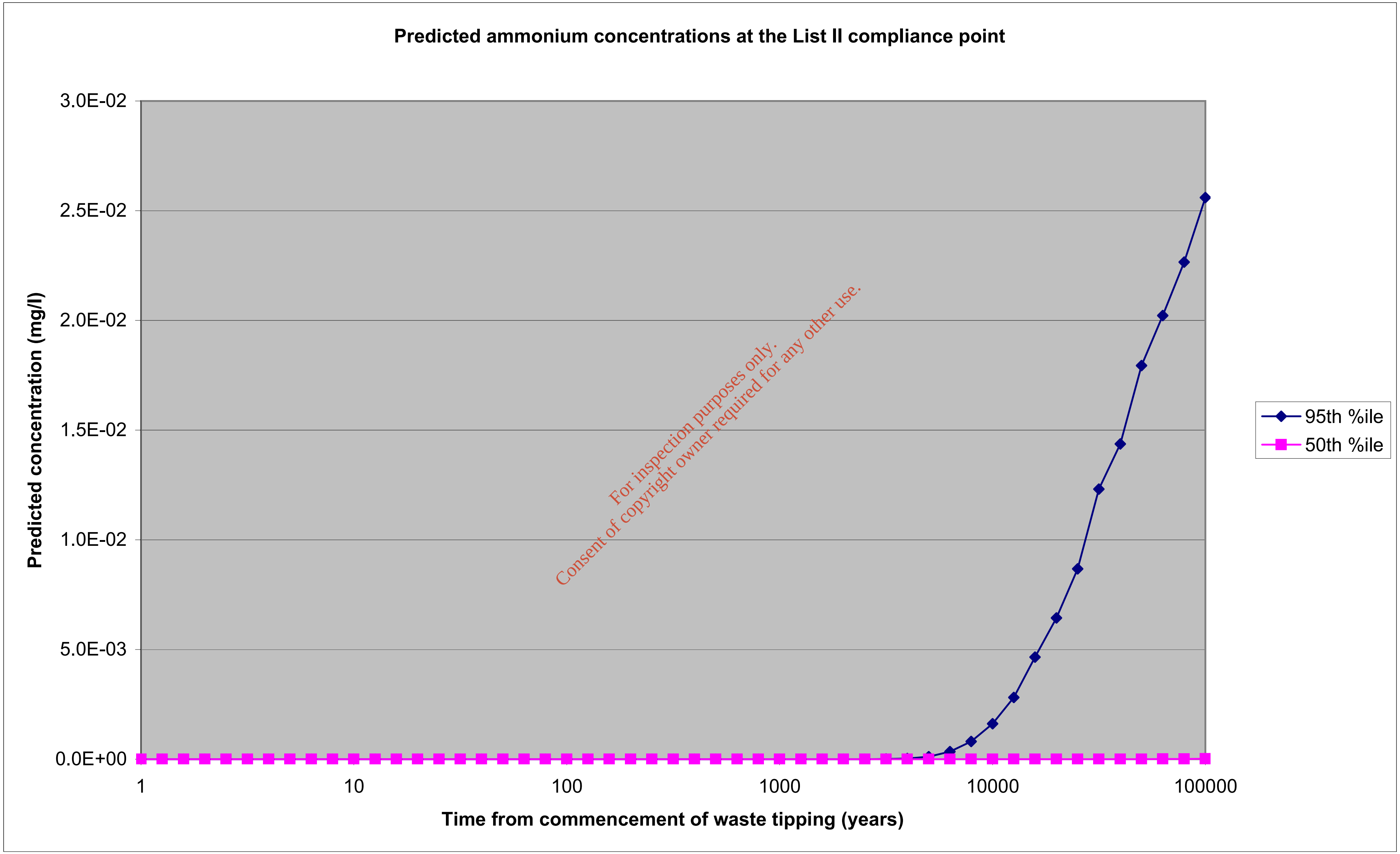
At infinity

05% of values less than 0
10% of values less than 3.41151E-012
50% of values less than 1.00189E-008
90% of values less than 1.08025E-006
95% of values less than 2.30718E-006

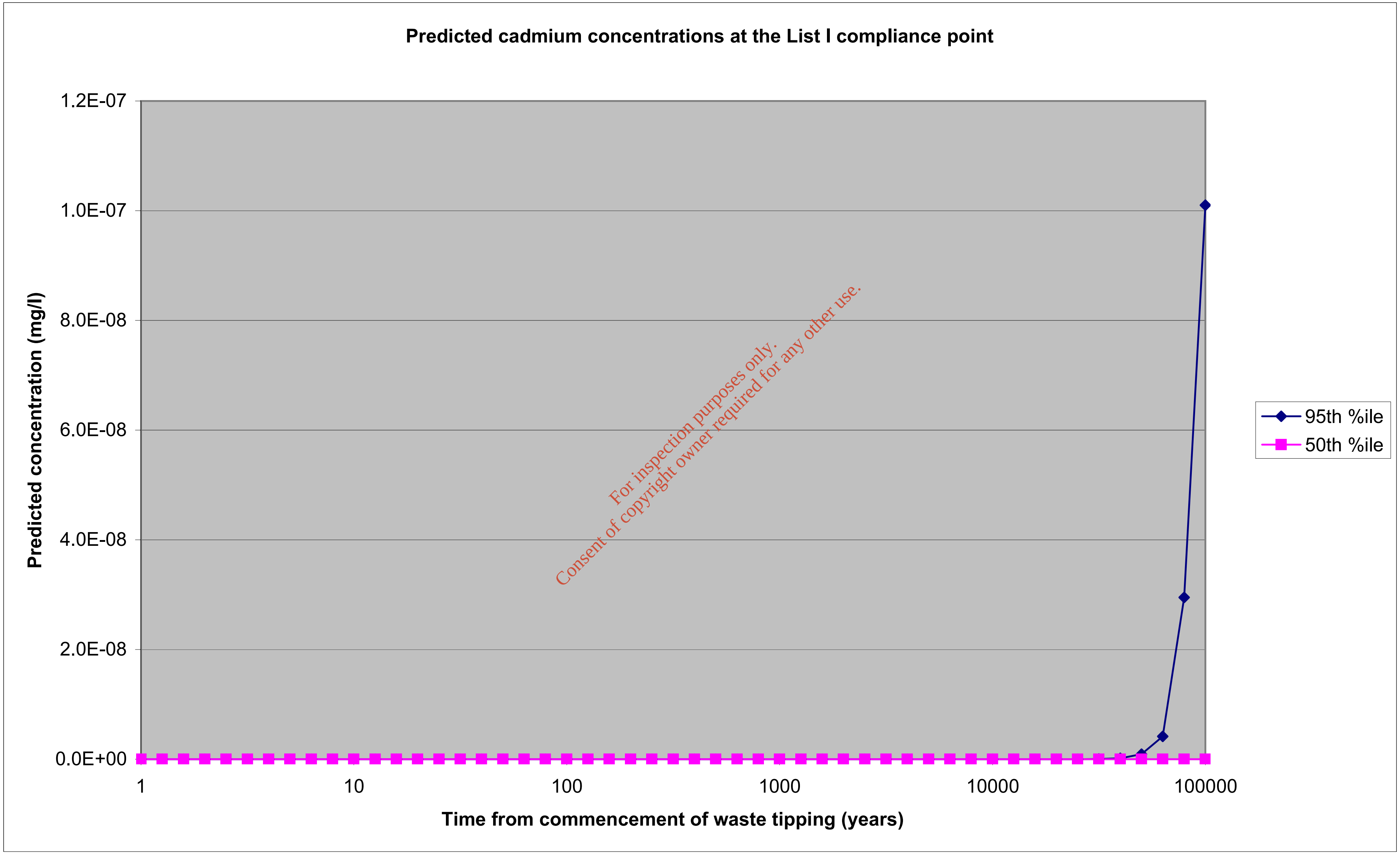
Minimum 0	Maximum 1.21065E-005	
Mean 4.08444E-007	Std. Dev. 1.30969E-006	Variance 1.7153E-012

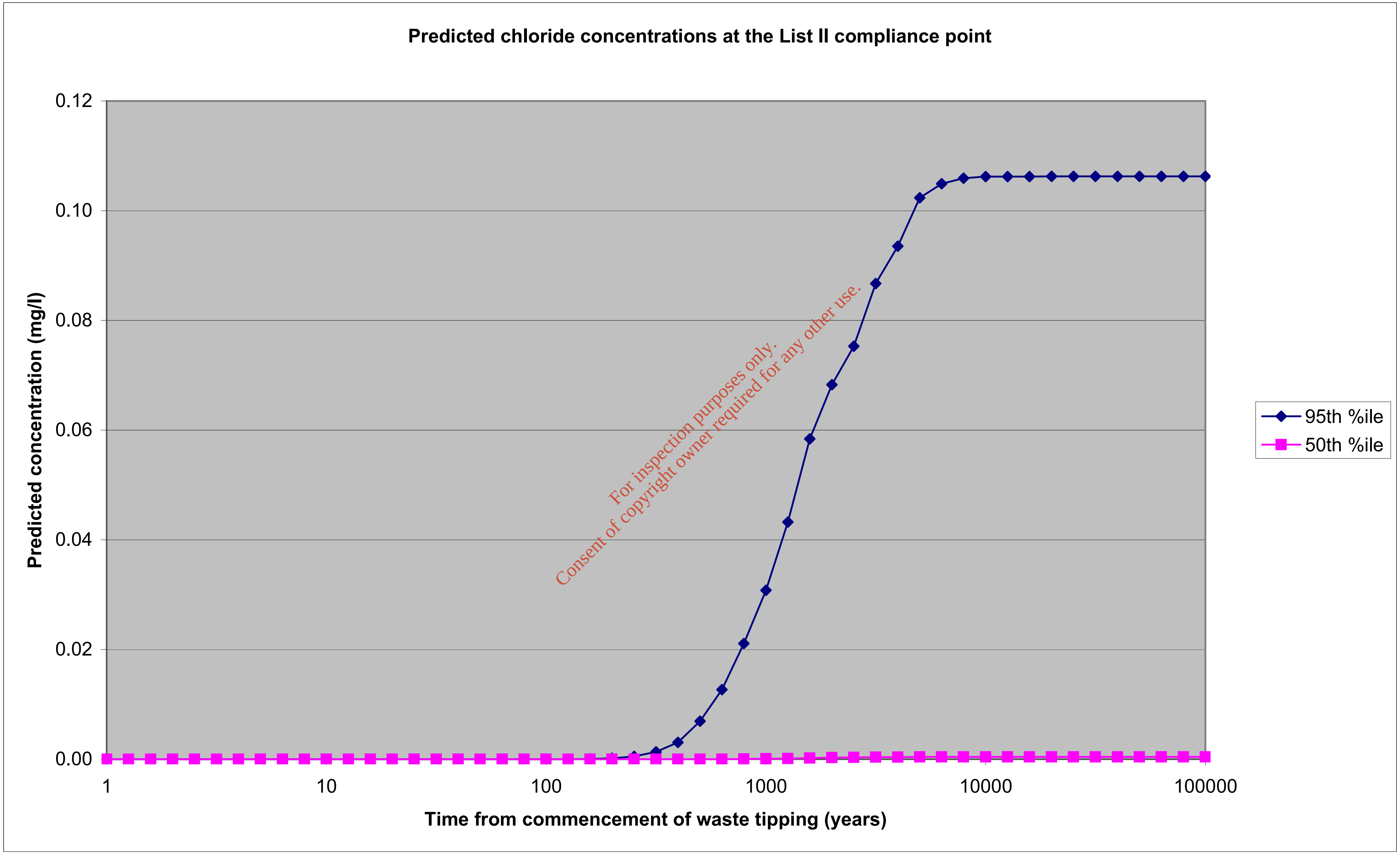
APPENDIX E2

OUTPUTS FROM DIFFUSION MODEL

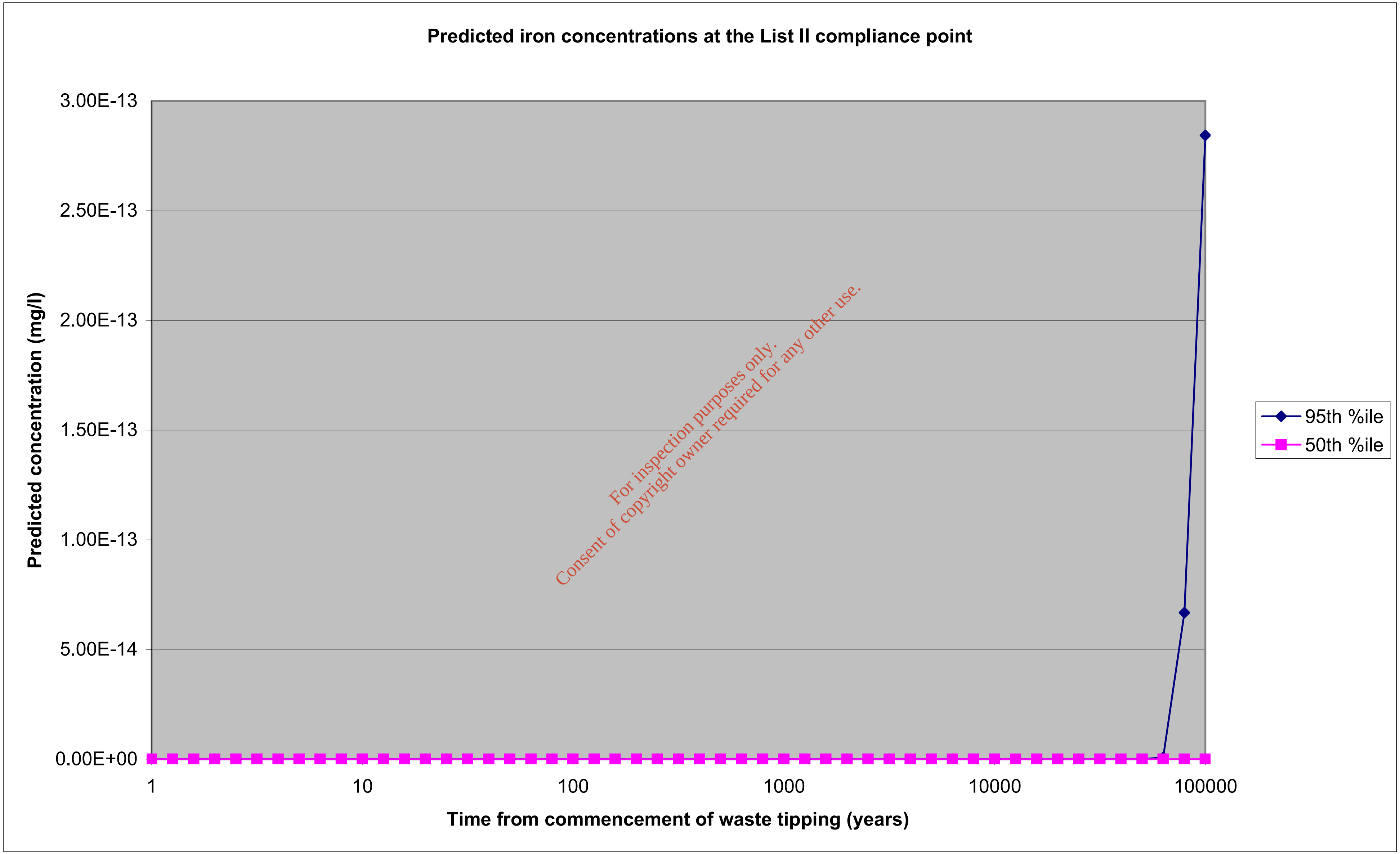


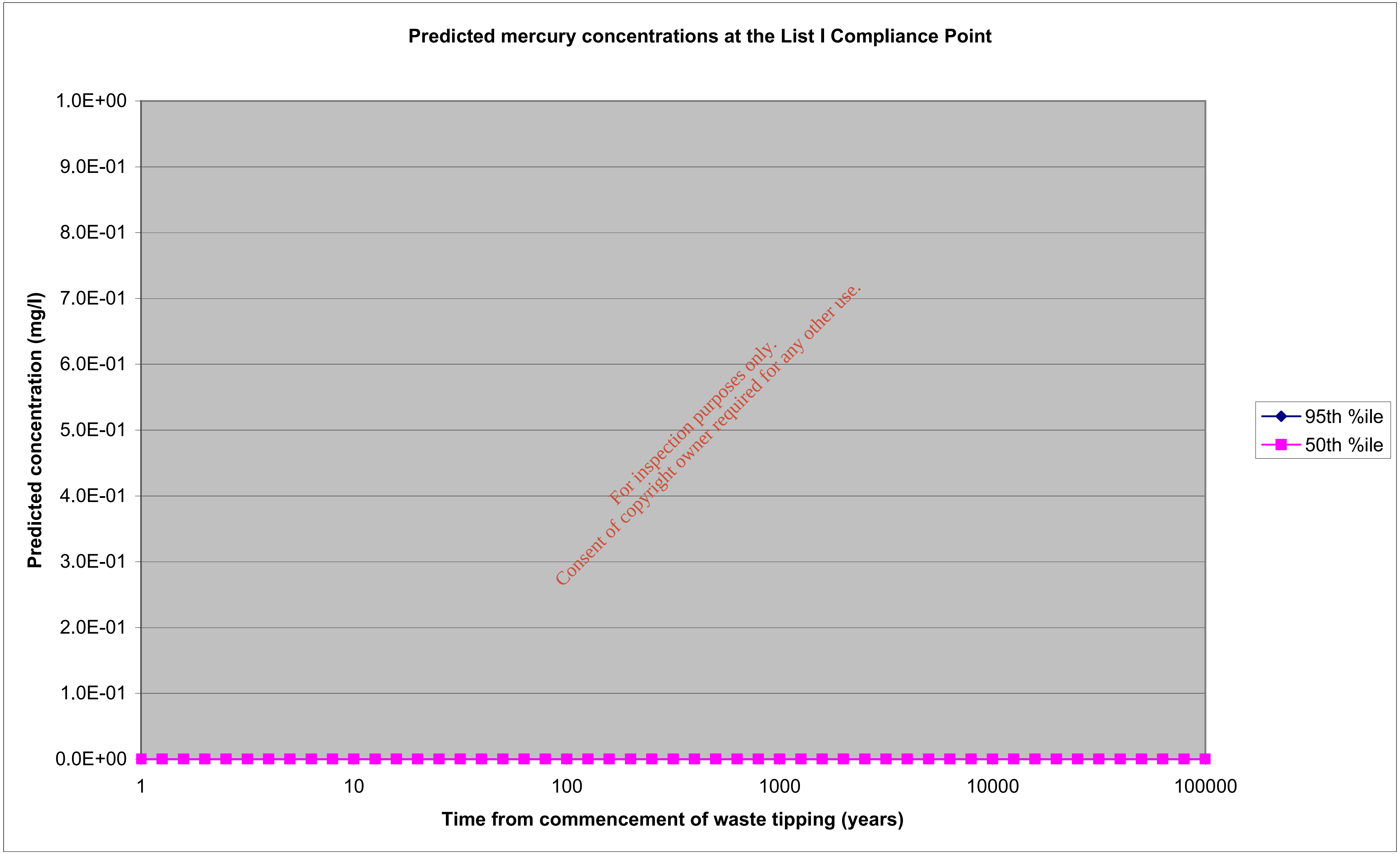
Predicted ammonium concentrations at the List II compliance point
3.0E-02
2.5E-02
2.0E-02
1.5E-02
1.0E-02
5.0E-03
0.0E+00
Predicted concentration (mg/l)
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile

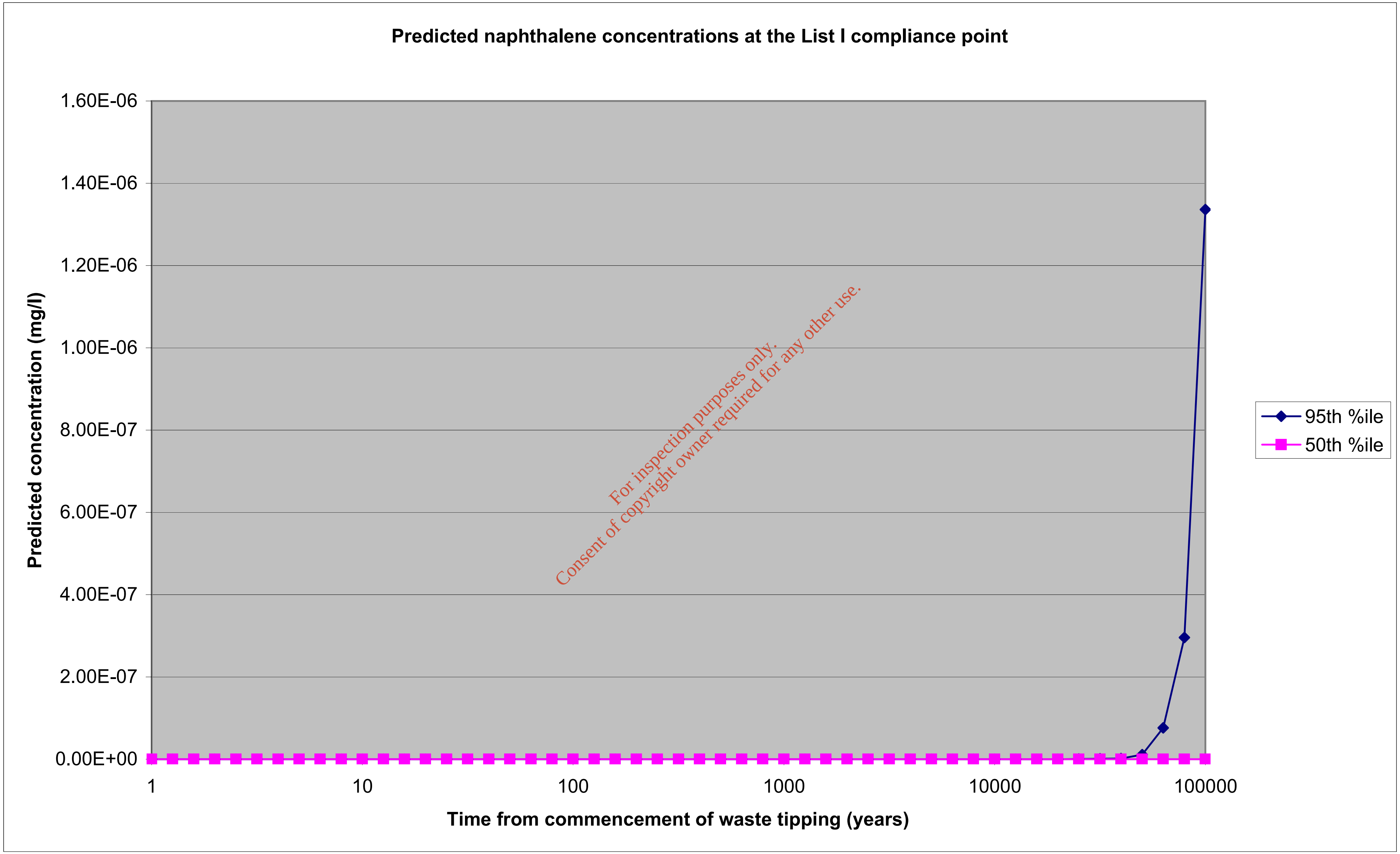

Predicted cadmium concentrations at the List I compliance point
Predicted concentration (mg/l)
1.2E-07
1.0E-07
8.0E-08
6.0E-08
4.0E-08
2.0E-08
0.0E+00
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile

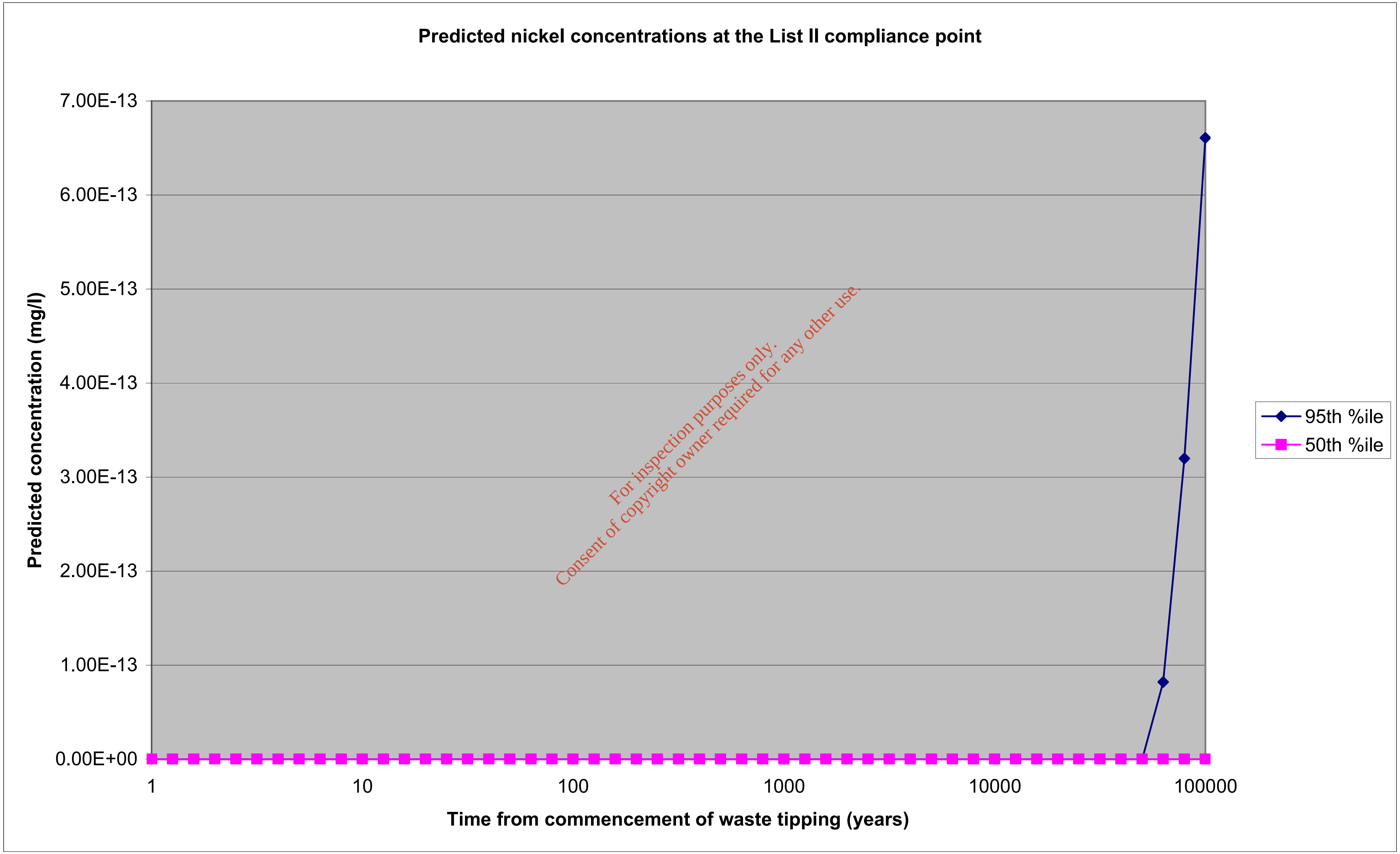


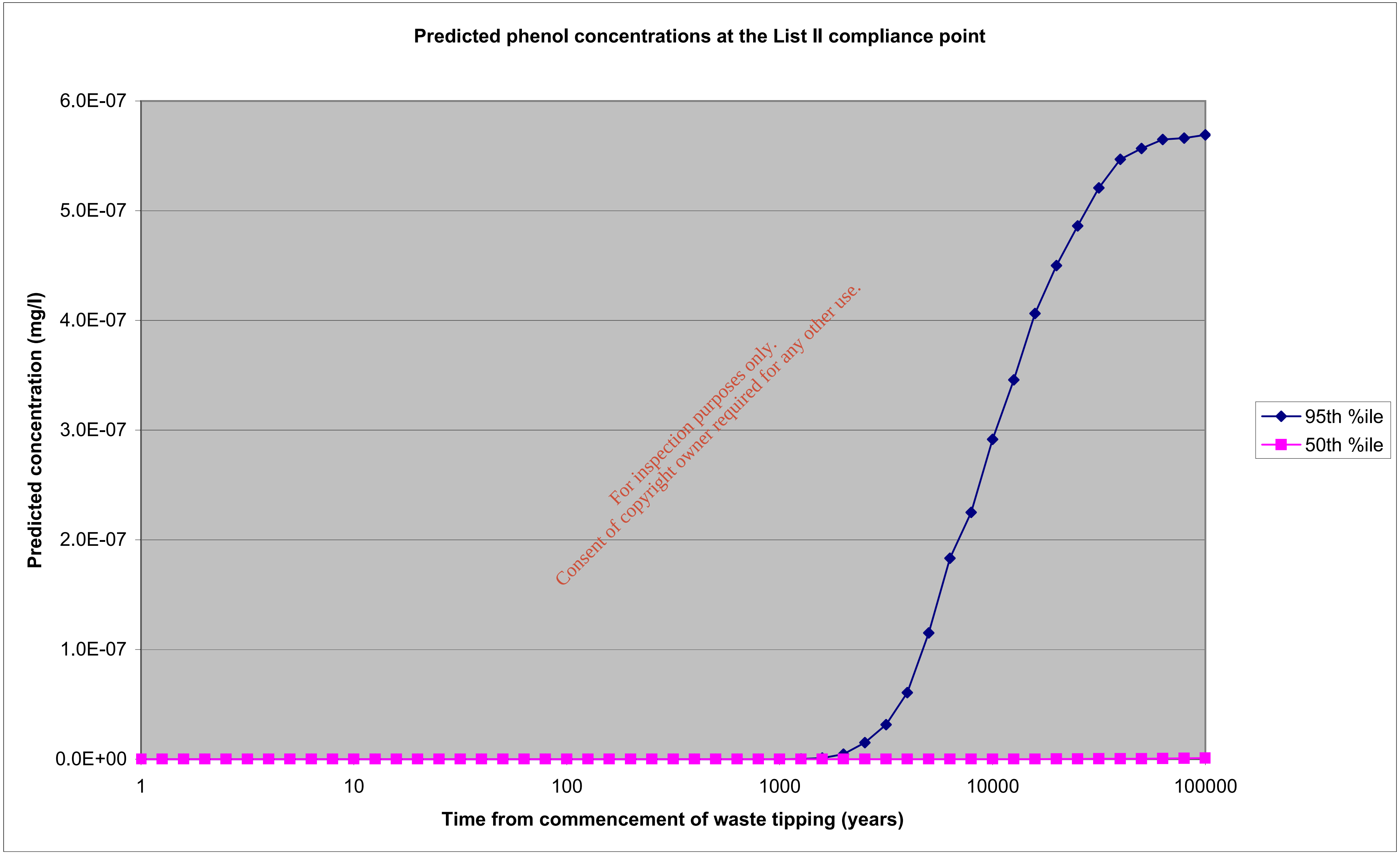
Predicted chloride concentrations at the List II compliance point
Predicted concentration (mg/l)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile

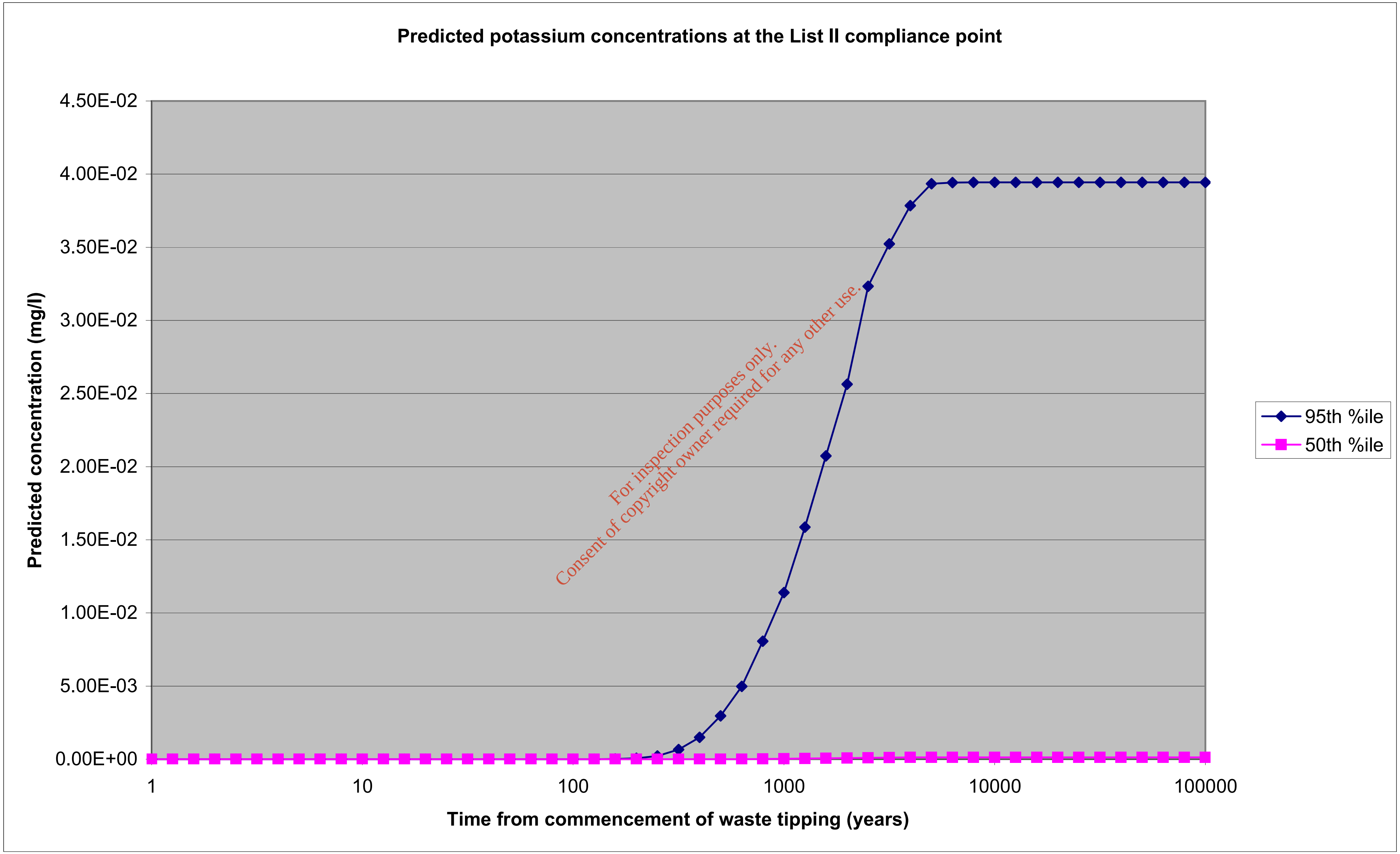

Predicted iron concentrations at the List II compliance point
3.00E-13
2.50E-13
2.00E-13
1.50E-13
1.00E-13
5.00E-14
0.00E+00
Predicted concentration (mg/l)
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile


Predicted mercury concentrations at the List I Compliance Point
1.0E+00
9.0E-01
8.0E-01
7.0E-01
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
0.0E+00
Predicted concentration (mg/l)
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile


Predicted naphthalene concentrations at the List I compliance point
Predicted concentration (mg/l)
1.60E-06
1.40E-06
1.20E-06
1.00E-06
8.00E-07
6.00E-07
4.00E-07
2.00E-07
0.00E+00
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile


Predicted nickel concentrations at the List II compliance point
Predicted concentration (mg/l)
7.00E-13
6.00E-13
5.00E-13
4.00E-13
3.00E-13
2.00E-13
1.00E-13
0.00E+00
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile
For inspection purposes only.
Consent of copyright owner required for any other use.


Predicted phenol concentrations at the List II compliance point
6.0E-07
5.0E-07
4.0E-07
3.0E-07
2.0E-07
1.0E-07
0.0E+00
Predicted concentration (mg/l)
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile



Predicted potassium concentrations at the List II compliance point
Predicted concentration (mg/l)
4.50E-02
4.00E-02
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
1
10
100
1000
10000
100000
Time from commencement of waste tipping (years)
95th %ile
50th %ile