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The Development of LandSim 2.5

National Groundwater and Contaminated Land Centre

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ENVIRONMENT AGENCY

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Statement of use:
This report explains the development of the LandSim 2.5 groundwater risk assessment tool for landfill design. It includes a scoping report outlining the changes proposed from the previous version (LandSim 2.02), the data from experimental leaching tests used to define the new declining source term, and the results of a comparison exercise between LandSim 2.02 and version 2.5.

Executive Summary

This document contains three individual reports that detail the work undertaken during the development and testing of LandSim 2.5. The three parts are: Part A – Scoping study for the development of LandSim 2.5; Part B – Leach testing of municipal solid waste; and Part C – Comparison of LandSim 2.02 with LandSim 2.5.

These three reports describe distinct sections of the LandSim 2.5 project and are presented as stand-alone documents. Each report therefore contains a table of contents, reference list, appendices etc. and has been separately paginated (e.g. Part A-1, Part B-1, Part C-1). To aid the reader, the individual Executive Summary from each report has been reproduced below.

Part A – Scoping study for the development of LandSim 2.5

The Environment Agency requested Golder Associates (UK) Limited to upgrade LandSim to improve the representation of the leachate source, and so that during groundwater risk assessments, failure and degradation of active controls of engineered landfill sites can be taken into account. This report scopes the work required to upgrade LandSim.

Leachate source

The current use of spot measurements of leachate quality to define the initial concentration of species results in the overestimation of the strength of the source. The overestimation of the initial concentration of leachate species not on List I can be minimised by using data representative of average leachate quality. Data have been collected from landfills where both spot measurements of leachate quality and measurements of bulk leachate quality exist. Probability density functions of the spot measurements have been sampled a number of times and the values averaged. Once the spot measurements have been sampled seven times and averaged, the resulting distribution is sufficiently close to the distribution of bulk leachate quality data even at extreme percentiles. It is recommended that the dialogue box describing the leachate source be modified to include a tick box for species not on List I so a user can identify whether the range of concentration relates to spot measurements of leachate quality or bulk leachate quality. Where spot measurements of leachate quality are input, the initial concentration of species not on List I, should be calculated from the average of seven values sampled from the distribution.

The way in which the concentration of species changes with time should depend on the whether the species are volatile. The removal of volatile compounds via landfill gas results in a declining concentration in the gas and leachate phases. Data describing the concentration of four volatile organic compounds in leachate has been analysed. The analysis suggests a reduction in concentration with a half-life of ten years is appropriate.

A species specific means of simulating the change in concentration of non-volatile organic compounds was recently presented at the EU Technical Adaptation Committee dealing with the Landfill Directive. The rate of change in concentration is determined by a species specific kappa value. Over two thousand kappa values for different species in different waste types were collated. Analysis of the data has found that a single kappa range cannot be established for each species, that would adequately represent all types of waste. A strong correlation was identified between the initial concentration of a species in leachate and the value of kappa. The results of a simulation of leachate concentration using both a constant value for kappa (calculated using the initial leachate concentration) and a concentration dependent value for kappa demonstrated that the difference in predicted concentration is generally small. It is therefore recommended that the kappa values should be calculated using the initial concentration of each species in leachate and remain constant throughout a simulation.

Failure and degradation of active controls of engineered landfill sites

A brief review of literature was carried out to identify physical and chemical processes that would result in the degradation of engineered landfill caps and artificial sealing liners.

It is assumed that any reduction in cap performance would be repaired during the period of institutional/operational control and that degradation processes, if they occur, would only result in an increase in infiltration of rainfall to waste after this period elapsed. No processes were identified that would result in the degradation of mineral and geosynthetic clay liner (GCL) caps. Oxidation of FML caps would result in an increase in infiltration that, in the absence of other indications, is assumed to be linear.

Two types of artificial sealing liners were considered – flexible membrane liners (FMLs) and dense asphaltic concrete (DAC). The literature suggests that FMLs degrade by oxidation that results in the exponential reduction of engineered performance. The information presently available suggests that DAC is likely to be robust in the landfill environment. DAC is likely to eventually degrade by oxidative ageing but there is no information in the literature reviewed to quantify its longevity.

A numerical model was constructed to simulate the degradation of landfill caps and artificial sealing liners, and the cessation of institutional/operational control. An analysis of the sensitivity of the predicted groundwater quality to choices of conceptual model and parameter value was carried out.

On the basis of the literature review and sensitivity study it was recommended that neither the degradation of mineral or GCL caps should be simulated in LandSim 2.5. The degradation of FML caps should be simulated with a linear increase in infiltration between certain specific start and end times. Based on the literature review, the default values for these times are 250 years and 1000 years post construction, respectively.

The degradation of FML artificial sealing liners should be simulated by doubling the area of existing defects over a fixed period of time. From the literature review, the default value for the area of defects to double is 100 years, with degradation commencing 150 years post construction. The number of defects in FML artificial sealing liners should be increased from the time of construction until the onset of degradation.

After reviewing the literature, it was recommended that LandSim 2.5 should not include degradation of DAC.

The ending of institutional/operational control should result in the leachate head varying according to a balance of inflow of water and leakage of leachate from the landfill.

Recommendations are made as to the best way to control the numerical stability and accuracy of the simulation.

Other changes to LandSim

It was proposed to:

- minimise the overly conservative predictions of concentrations at extreme percentiles by allowing the user to express uncertainty in Darcy flux instead of both saturated zone hydraulic conductivity and hydraulic gradient;

- modify the model to allow simulation of geochemical processes of advection, dispersion, partition and biodegradation in the wetted mineral part of basal lining systems to permit more realistic calculation of contaminant transport times and concentration at compliance points; and

- remove the process of irreversible sorption from the model.

Part B – Leach testing of municipal solid waste

Part B of this report describes the commissioning and interpretation of leach tests on samples of municipal solid waste. LandSim 2.5 uses a revised method of modelling a contaminant specific declining source term. The method was taken from that developed during the TAC Modelling Group for Waste Acceptance Criteria (WAC) (Hjelmar et al, 2001). The rate at which the concentration of contaminants changes is controlled by the variation of liquid/solid ratio and a parameter known as kappa. The leach tests were undertaken to derive kappa values for ammonium and other contaminant species.

Five samples of pulverised municipal solid waste were subjected to an upward flow percolation test in accordance with the draft CEN percolation simulation test. For each of these percolation tests, seven leachate samples were collected at different liquid solid ratios and analysed for species that define the WAC and ammonium. Kappa values were calculated from the laboratory results and are presented in Table 1. The kappa values are broadly consistent with a larger dataset supplied by the Energy Research Centre of the Netherlands (pers. comm. Van der Sloot, 2002). Notable anomalies are lead and antimony, which appear to be more readily flushed from MSW than would have been predicted from the larger dataset.

Part C – Comparison of LandSim 2.02 with LandSim 2.5

Part C of this report presents the results of an exercise to compare the predictions of LandSim 2.02 and the proposed LandSim 2.5.

The predictions of the two versions of the model were compared by simulating the migration of four contaminants with diverse behaviours, from an engineered landfill site. The publicly available version of LandSim 2.02 and a development version of LandSim 2.5 were used.

The results of the comparison exercise are shown in Figures 1 to 5. The comparison demonstrated that LandSim 2.5 will predict much more rapid reduction in the leachate concentration of volatile contaminants and thereby lower concentrations at the water table than LandSim 2.02. The proposed changes to the way that the initial concentration of species not on List 1 is calculated and the way that the change in concentration of non-volatile species will be simulated are considered to add realism to the model, but not to have dramatic effects on predictions.

LandSim 2.5 allows the simulation of degradation of engineering and cessation of institutional/operational control. It is the simulation of the ending of institutional/operational control that has the most pronounced effect on the changes in predicted concentration. It is likely to result in higher predicted concentrations of mobile species and those contaminants whose effects at receptors are mitigated by processes, such as biodegradation, that rely on extended travel times.

Keywords
Landfill, leachate, groundwater risk assessment, LandSim, kappa

Part A

Scoping study for the development of LandSim 2.5

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1.0 Introduction

1.1   Background to this report

An assessment of the risk to groundwater quality is required of landfills regulated under the PPC Regulations 2000 or Waste Management Licensing Regulations 1994.

A sophisticated way of simulating the change in landfill leachate quality with time was developed during negotiations with the EU Technical Adaptation Committee, who dealt with Annex 2 of the Landfill Directive to derive waste acceptance criteria.

In light of the Landfill Directive's requirements that the risks to the environment throughout the lifetime of the site to be taken into account, the Environment Agency's Landfill Directive Regulatory Guidance Note 6 states "The risk assessment must take account of future failure and degradation of the active controls (e.g. artificial sealing liner and leachate drainage systems, and operational/management controls) as well as the likely contaminant concentrations in the landfill when failure/degradation occurs".

The Environment Agency has therefore requested that LandSim, a computer model that is used to assess risk to groundwater quality from landfill sites, is upgraded so that account can be taken of recent developments in the simulation of leachate quality and of failure and degradation of active controls.

1.2   Purpose and aims of the report

The purpose of this part of the report is to scope the work required to upgrade LandSim. It aims to:

- justify how conservatism in the derivation of the initial concentration of leachate can be reduced;
- describe the way that the concentration of non-volatile species can be simulated;
- describe the development of a method for simulating the change in concentration of volatile species;
- describe a brief review of literature concerning engineering longevity;
- describe the conceptual model for failure and degradation of active controls;
- describe the construction of a numerical representation of the conceptual model in a flexible simulation environment;
- describe an analysis of the sensitivity of the predicted groundwater quality to choices of conceptual model and parameter value;
- document other minor changes to LandSim.

1.3   Report structure

The report is divided into three parts: Part 1 (Section 2 to Section 4) deals with proposed changes to the leachate source, Part 2 (Section 5 to Section 8) describes the development of the way that engineering longevity is proposed to be simulated and Part 3 (Section 9) documents minor changes to LandSim.

Section 2 of this report follows this introduction and describes how it is proposed to simulate the initial concentration of species in leachate that are not on List I. The way it is proposed to simulate the change in leachate quality depends whether species are volatile. The proposed method of simulating the change in concentration of non-volatile species is described in Section 3. Section 4 describes the proposed method of simulating the change in concentration of volatile species.

Section 5 summarises a review of literature concerning engineering longevity. The review has been used to construct a conceptual model of the way the hydraulic performance of a landfill will change

over time (Section 6). Section 7 describes how the conceptual model has been transformed to a numerical model in GoldSim, a flexible simulation environment. The model has been used to assess the sensitivity of the predicted groundwater quality to choices of conceptual model and parameter value. This is summarised in Section 8.

Section 9 describes other changes that are proposed be made to LandSim.

Conclusions of the study are presented in Section 10 and recommendations in Section 11.

2.0 Simulating the initial concentration of species not on list I

2.1 Current representation of initial source concentration in Landsim v2

Versions 1 and 2 of LandSim use the same approach to define uncertainty in the initial concentration of contaminants in landfill leachate. The method involves the review of all data from a specific landfill (if the site is an existing landfill) or the use of default data generated by examining a large volume of leachate analyses (Robinson, 1995). A review to check the validity of results from LandSim v2 showed that the model quite accurately reflected real monitoring data in the mid-percentiles, but that it overestimated the impact at the high percentiles (especially those above the 90th percentile). Given the need to be inherently cautious in the interpretation of model results (knowing that the model did not consider long term degradation of the engineering of sites) it was considered that this overestimation was both appropriate and desirable in terms of environmental protection.

However, it was recognised that the model was over predicting impact (on the assumption that the engineering systems continue to perform as designed) and this discrepancy has lead to some loss of faith in the model's ability to make realistic predictions. With this revised version of LandSim (v2.5) an attempt has been made to understand the reasons why the initial approach adopted for defining the source term over predicts impact.

During a simulation, the probability density function (PDF) containing the entire range of possible concentrations of any specific contaminant is sampled and (for that iteration) applied to the entire site, irrespective of the number of cells it might be comprised of. In reality, it is improbable that the entire site will, at any time, contain leachate at a uniform strength. It is far more likely that each part of the site will contain leachate that is at varying strengths. Given that the impact of substances that are not on List I is measured in groundwater downstream of the site, it is reasonable to assume that a degree of mixing or averaging of the impact of different strength leachate will have occurred at the point of measurement. It is therefore likely that this is one of the contributory reasons for the current overestimate of impact predicted with version 2 of the model.

2.2 Methodology to address averaging of variability in initial source concentration

Data have been obtained from site operators for sites where there was a reasonable spread of data from both leachate monitoring points (leachate wells and gas wells) in addition to bulk leachate samples obtained from leachate extraction systems. Because the representative volume of leachate being sampled in the static monitoring points is small and that of the leachate extraction system large, we can expect the latter to provide a better indication of the averaging effect that might better reflect the leachate strength that should be used for defining the source term. One would expect that the degree of variation in leachate strengths from spot samples would be greater than those derived from bulk leachate samples taken from the influent to a leachate treatment system, discharged to a tanker for off-site disposal, or an untreated discharge to sewer.

2.3 Development of methodology to sample spot measurements

We have considered only chloride and ammoniacal nitrogen within the numerical analyses that we have undertaken on the basis that these two parameters are the most common determinands beyond electrical conductivity and pH (neither of which would normally be considered by a groundwater risk assessment). In total we have examined data from six sites although we only have chloride data for four of these. We have taken the raw leachate data (from both spot readings and from bulk leachate) and developed PDFs in the same way that would be developed when setting up a LandSim model. Virtually all the data was taken at face value, with only two or three data points being rejected. These rejected data relate to such things as the first leachate sample from a leachate lagoon where it was evident that the leachate quality was heavily diluted. Only very low values were rejected.

On the whole, larger data sets are likely to be more reliable than small data sets, and other factors that might complicate the picture (such as areas where leachate is pumped from one area of a site to another) have been avoided where possible.

Tables 1 and 2 present a summary of the data collated.

Table 1: Chloride PDFs from different sampling points

Site	Sample Type	Distribution Determined	Minimum (mg/l)	Most likely (mg/l)	Maximum (mg/l)
Site A	Leachate Wells	Log Triangular	130	894	2345
	Discharge to Lagoon	Log Triangular	213	528	1309
Site B	Leachate Wells	Triangular	1684	5054	7301
	Discharge to Lagoon	Triangular	3546	5314	5314
Site C	Leachate Wells	Log Triangular	268	2030	3045
	Discharge to Lagoon	Log Triangular	248	1367	2095
Site D	Leachate Wells	Log Triangular	148	1700	3310
	Discharge to Lagoon	Log Triangular	340	1681	2113

Table 2: Ammoniacal nitrogen PDFs from Different Sampling Points

Site	Sample Type	Distribution Determined	Minimum (mg/l)	Most likely (mg/l)	Maximum (mg/l)
Site A	Leachate Wells	Log Triangular	32	1268	1268
	Discharge to Lagoon	Log Triangular	75	698	1055
Site B	Leachate Wells	Log Triangular	130	1045	5462
	Discharge to Lagoon	Log Triangular	263	413	602
Site C	Leachate Wells	Log Triangular	511	1260	1580
	Discharge to Lagoon	Log Triangular	831	1014	1121
Site D	Leachate Wells	Log Triangular	443	1900	2730
	Discharge to Lagoon	Log Triangular	888	1175	1352
Site E	Leachate Wells	Log Triangular	40	2068	2068
	Discharge to Lagoon	Log Triangular	52	761	1489
Site F	Leachate Wells	Log Triangular	211	710	1595
	Discharge to Lagoon	Log Triangular	221	705	1037

There were 565 individual leachate analyses for chloride in the data set; of which 329 values were of spot readings and 236 values from discharge data. There were 1400 individual leachate analyses for ammoniacal nitrogen, of which the number of spot and bulk measurements were similar. In all cases the data range for the spot readings was larger than the data range of the discharge data. The only slight anomaly in the chloride data was at Site C where the minimum value determined from the data set relating to the discharge is slightly lower than the minimum value determined from the spot readings. The decrease in the range for the leachate discharges varies from a factor of 1.5 to 3 less than the spot readings for the chloride data and ranges from 1.3 to 5 from ammoniacal nitrogen (with an anomalous value of 15 for Site B). These in their own right are quite significant decreases, but the largest impact is in the reduction of the extreme values, which is often the cause of the overestimation of impact within LandSim v2.

2.4   Development of a methodology to sample spot measurements

It is apparent that where there is bulk leachate collection and analyses from an existing site, these data should be used in preference to spot monitoring results from leachate wells. However, for sites where leachate extraction is not occurring, or where there are no reliable data upon which to generate PDFs from the leachate discharge, there needs to be an alternate method for redefining the PDF generated from raw spot readings into a PDF which more readily represents the sort of averaging that we see in bulk leachate chemistry.

If a specific PDF is repeatedly sampled and the results averaged (giving them equal weight) ultimately the mean of the distribution will be obtained. However, this would require a very large number of

repeated samplings, and it is not desirable to simply model on the basis of the mean, because uncertainty in the mean should be taken into consideration. If the bulk samples are truly a sub-set of the spot measurements, then they should have the same mean as the spot measurements, but the extreme values (both high and low) will be greater in the spot samples. By sampling the spot sample distributions a small number of times (two to ten times) and averaging the selected values, the resultant distribution should ultimately share the same range and percentiles as the bulk sample. This was attempted with the data obtained from the six landfill sites for which there was detailed information.

Table 3 shows the resultant percentiles for Site A, with the values for both the discharge and then the results of sampling a PDF of the spot readings, and averaging the results, from between 1 to 7 times. The range of values for the bulk leachate (labelled Discharge) is from 220 to 1,239 mg/l. The range generated from sampling the spot measurements over the same number of iterations (1000) is 148 to 2314 mg/l. However, this range reduced to 331 to 1,347 mg/l after sampling the spot measurements distribution seven times on each iteration and averaging the results.

For pure calibration purposes, a close fit at the mean is needed. This sampling indicates (for this example) that there is a difference in the calculated mean value that has essentially stabilised after sampling the distribution three times. This is not ideal. However, the 90th and 100th percentiles (the range that includes the concentrations that will often drive the risk assessment) converge quite closely to the bulk leachate data after sampling the distribution six or seven times. In addition to Table 3, graphical representation of the distributions (shown as cumulative curves) is presented in Appendix 1 for each of the sites.

Table 3: Chloride Data Site A - Percentiles following multiple sampling

Site A	Discharge	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	Spot 6	Spot 7
0%	220	148	176	192	235	242	277	331
10%	322	284	359	409	440	453	473	487
20%	380	388	438	478	503	518	532	535
30%	432	482	514	535	555	561	570	577
40%	482	592	588	587	607	605	613	616
50%	536	696	657	647	651	651	655	652
60%	588	803	731	707	699	692	698	696
70%	657	930	806	770	749	752	741	736
80%	754	1,094	927	846	818	812	795	790
90%	896	1,388	1,093	979	927	895	883	861
100%	1,239	2,314	1,783	1,579	1,479	1,589	1,420	1,347
Mean	574	767	697	677	669	668	668	667

It appears that the majority of distributions are well matched at the upper percentiles after between 2 and 10 re-samplings of the initial distributions. The data fit is not always perfect, but in all cases those with the worst fit were obtained from sites where the pattern of leachate management was more complex, with leachate recirculation and in some cases quite evident dilution of leachate in the leachate collection system. The latter was a feature especially at sites where leachate has been collected from peripheral drains rather than from sumps within leachate drainage blankets.

It is also evident that while the upper percentiles can be matched quite closely, it is often the case that the mean is not matched between the spot data and the bulk leachate quality measured at the point of discharge. Indeed, at the P=0.05 level, t tests have demonstrated that the difference between the mean of the spot data and mean of the discharge data is significant for chloride at Site A and Site C and ammoniacal nitrogen at Site B and Site F. This feature was looked at to determine if there was a specific trend that could be used to further refine the method. While the majority of curves came within plus or minus 13% of the mean (accounting for both positive and negative effects), for chloride the average error from all of the analyses was +0.7% and for ammoniacal nitrogen the average error was +1.4%. The plus sign means that the total mass of contaminant being represented by the bulk

discharge data is greater than that indicated by the spot readings. It therefore appears that while each site contains some bias to the data, the overall effect is very near to neutral.

A further issue that was examined is that relating to the number of re-samplings of a distribution that is required to match the discharge data. It was anticipated that the convergence would be related to the size of the cell (or cells) that were being sampled within any specific sample set. However, no clear relationship can be determined.

2.5   Recommendations for simulating the initial concentration of species not on List I

It is apparent from the assessment of the spot measurements of leachate quality and corresponding bulk leachate quality that where there is bulk leachate collection and analyses from an existing site, these data should be used in preference to spot monitoring results from leachate wells.

Where leachate data relating to substances that are not on List I are obtained solely from spot measurements within a landfill, the PDF that is generated from the data set should be internally sampled within LandSim seven times in order to attempt to replicate the true averaging that is likely to occur as a result of spatial variations and mixing, within the aquifer, of leachate that has leaked from different locations.

The current default data contained within LandSim and an example of the distribution that LandSim would realise after 1,000 iterations are presented in Table 4.

Table 4: Existing and proposed contaminant distributions

Contaminants	Original Distributions (mg/l)			Revised Distributions (mg/l)		
	Minimum	**Most likely**	**Maximum**	**Minimum**	**Most likely**	**Maximum**
Ammoniacal nitrogen	4.37	723	3640	32.1	267	1100
Arsenic	0.000673	0.00484	1.31	0.00371	0.00485	0.0107
Chloride	36.6	2270	7760	227	997	2650
Chromium	0.00856	0.0647	1.75	0.0231	0.0981	0.416
Copper	0.00489	0.0243	1.13	0.0129	0.0509	0.191
Lead	0.00957	0.130	1.02	0.0337	0.111	0.340
Nickel	0.00883	0.120	2.21	0.0345	0.126	0.627
Potassium	7.55	929	3120	40.8	321	1140
Zinc	0.00225	0.165	208	0.0296	0.362	9.00

3.0 Simulating the change in concentration of non-volatile species

3.1 Background

The change in concentration of contaminants in leachate in LandSim v2 depends on the ratio of the volume of infiltration to the total field capacity of the waste. The rate of change of concentration is the same for all contaminant species. A methodology presented by H. A. van der Sloot, at the EU Technical Adaptation Committee dealing with the Landfill Directive, improves the approach and is contaminant specific (Hjelmar et al 2001). The concentration of a species at any time, C(t), is determined from:

$$C(t) = C_0 \, e^{-(\kappa * LS)}$$

Where:

C_0 is the initial concentration of the species in leachate, usually determined when LS = 0.1 l/kg (mg/l).

κ (kappa) is a species and waste specific parameter (kg/l).

LS is the liquid/solid ratio at time t (l/kg).

The liquid/solid ratio at any time is calculated by dividing the infiltration in to the waste up to that time by the mass of waste. It therefore time dependent and increases throughout the life of a landfill.

Whilst the initial concentration and liquid/solid ratio can be readily determined from the site design, the value of kappa (κ) has to be derived from laboratory column percolation leaching experiments. A contaminant species with a high value of kappa is leached more rapidly than a species with a low value of kappa, and its concentration in leachate will decrease more rapidly.

3.2 Collation of kappa values

H. A. van der Sloot, at the Energy Research Centre of the Netherlands (ECN), has supplied 2007 experimentally derived values for kappa for several types of solid waste and soils. The kappa values have been determined from column leach tests. The purpose of collecting these data was to investigate how kappa may be used in the development of a contaminant specific declining source term in LandSim v2.5. In order to develop a kappa driven source term it is important to understand the variability of kappa between both waste types and species and to investigate the relationship between kappa and contaminant concentrations within the solid and aqueous phases.

3.3 Assessment of a contaminant specific value of kappa

An assessment was made to determine whether there is a distinct range of values of kappa for individual contaminants; this was done by generating probability density functions and descriptive statistics for individual waste types using the collated data (Table 5). There were limited data for several of the waste types, and probability density functions and descriptive statistics could not be generated.

It is clear from the data that there is considerable variability between waste types for individual species. It was concluded from the analysis of the data, that a default kappa range cannot be established for use in LandSim 2.5, which would be adequately representative of all types of waste likely to be accepted at a landfill.

Table 5: Analysis of values of kappa for different contaminant species and waste

Kappa Values By Species								
	PDF			Extra Statistics				
Waste Type	Distribution	Min	Likely	Max	Min	Max	Mean	St Dev	Count
Copper									
C&D Mixed Aggregate	Triangular	0.31	0.38	0.53	0.31	0.53	0.37	0.069	9
C&D Crusher Sand	Uniform	0.29		0.49	0.29	0.49	0.38	0.08	9
Crusher Fine Sand	Triangular	0.14	0.45	0.45	0.14	0.45	0.31	0.11	14
MSWI - Bottom Ash	Triangular	0.086	0.47	0.85	0.086	0.85	0.44	0.15	38
Cleaned Soil	Log Triangular	0.069	0.28	0.63	0.025	0.63	0.22	0.13	22
Contaminated Soil	Log Triangular	0.026	0.14	0.47	0.044	0.47	0.094	0.11	29
C&D Waste	Triangular	0.25	0.43	0.43	0.25	0.43	0.36	0.052	10
Soil	Log Triangular	0.02	0.29	0.67	0.02	0.67	0.24	0.17	23
Fluoride									
C&D Mixed Aggregate	Triangular	0.14	0.51	0.51	0.14	0.51	0.35	0.15	8
C&D Crusher Sand	Triangular	0.023	0.48	0.71	0.023	0.71	0.35	0.21	9
LD Steel Slag	Log Triangular	0.011	0.17	1.28	-0.35	1.28	0.26	0.43	24
MSWI - Bottom Ash	Log Uniform	0.0059		0.58	0.0059	0.58	0.24	0.21	17
Sulphate									
C&D Mixed Aggregate	Uniform	0.07		0.37	0.07	0.37	0.2	0.13	8
MSWI - Bottom Ash	Uniform	0.18		0.49	0.18	0.49	0.33	0.098	23
Chromium									
Crusher Fine Sand	Triangular	0.17	0.43	0.43	0.17	0.43	0.34	0.078	11
MSWI - Bottom Ash	Triangular	0.081	0.32	0.56	-0.049	0.56	0.28	0.15	23
C&D Waste	Triangular	0.11	0.31	0.31	0.11	0.31	0.24	0.071	10
Soil	Log Uniform	0.11		0.36	-0.12	0.36	0.16	0.13	16
Barium									
LD Steel Slag	Log Triangular	0.036	0.53	0.53	-0.094	0.53	0.22	0.19	29
MSWI - Bottom Ash	Log Triangular	0.0058	0.15	0.15	-0.032	0.15	0.039	0.056	25
Soil	Triangular	0.037	0.42	0.81	0.037	0.42	0.81	0.16	23
Chloride									
LD Steel Slag	Triangular	0.08	0.66	1.24	-0.4	1.24	0.52	0.36	24
MSWI - Bottom Ash	Triangular	0.47	0.94	1.09	0.47	1.09	0.87	0.15	23
Zinc									
Cleaned Soil	Uniform	0.081		0.6	0.081	0.6	0.3	0.14	20
Contaminated Soil	Log Triangular	0.13	0.46	0.85	-0.037	0.85	0.29	0.18	32
MSWI - Fly Ash	Triangular	0.12	0.31	0.67	0.12	0.67	0.34	0.15	13
Soil	Log Triangular	0.07	0.49	0.91	-0.13	0.91	0.32	0.21	25
Molybdenum									
MSWI - Bottom Ash	Triangular	0.26	0.48	0.93	0.26	0.93	0.49	0.13	38
MSWI - Fly Ash	Triangular	0.24	0.38	0.67	0.24	0.67	0.39	0.13	14
Nickel									
MSWI - Bottom Ash	Uniform	0.049		0.66	0.049	0.66	0.34	0.19	17
Soil	Triangular	0.1	0.31	0.62	-0.1	0.62	0.19	0.19	19
Lead									
MSWI - Bottom Ash	Triangular	0.0038	0.58	0.77	-0.24	0.77	0.34	0.24	18
MSWI - Fly Ash	Triangular	0.22	0.49	1.02	0.22	1.02	0.55	0.23	13
Soil	Log Triangular	0.02	0.49	0.91	-0.05	0.66	0.2	0.16	23
Cadmium									
MSWI - Fly Ash	Triangular	0.49	1.51	1.51	0.49	1.51	1	0.31	13
Soil	Log Triangular	0.11	0.42	1.01	0.11	1.01	0.31	0.17	25

Table 5 Key

C & D   =   Construction and Demolition
MSWI   =   Municipal Solid Waste Incinerator
LD   =   Lintz Donawits

3.4   Assessment of the relationship between leachate concentration and kappa

The kappa value for any species is strongly influenced by the partitioning of the species between solid waste and leachate. The kappa values have been compared to the initial leachate concentrations derived from the column tests to determine whether the partitioning is linear, or whether there is a relationship between the value of kappa and the initial leachate concentration.

3.4.1   Methodology

Contaminant specific kappa values for all waste types were plotted against the initial leachate concentration of the contaminant of interest, as derived from the column test. The initial leachate concentration was determined by laboratory analysis of the first pore water removed from the sample (equivalent to a typical liquid/solid ratio of approximately 0.05).

The contaminants for which sufficient data existed to carry out the analysis were:

Arsenic	Copper	Lead	Vanadium	Total cyanide
Barium	Mercury	Antimony	Zinc	Free cyanide
Cadmium	Molybdenum	Selenium	Bromide	Fluoride
Chromium	Nickel	Tin	Chloride	Sulphate

3.4.2   Results of analysis

Figure 1 plots the derived kappa value from the column tests against initial concentration (μg/l) for Cadmium, Chromium and Molybdenum. The plots demonstrate the strong relationship between initial concentration and kappa. As a guide to the degree of correlation, the correlation coefficient (r^2) was determined for all species and is provided in Table 6 with the equation of the best logarithmic trend line through the data. The correlation coefficients for the linear regressions have been calculated using the Pearson formula. Those results that are not statistically significant at the P=0.05 level are shown in italics in Table 6. There is a positive correlation between the value of kappa and initial contaminant concentration, C_0 (μg/l), for all contaminants included in the study. The correlation coefficient ranges between 0.06 (sulphate) and 0.8 (free cyanide). Whilst the correlation for the chloride data was not significant at the P=0.05 level it is significant at the P=0.1 level.

Table 6: Correlation between Initial Concentration (C_0) and Value of Kappa

Contaminant	Kappa (kg/l)	Correlation Coefficient	Value of kappa (kg/l) using most likely concentration from Table 4 for C_0
Arsenic	*0.0415Ln(C_0) - 0.0862*	*0.09*	-0.020
Barium	0.0806Ln(C_0) - 0.2754	0.37	
Cadmium	0.0823Ln(C_0)+ 0.1589	0.66	
Chromium	0.0514Ln(C_0) + 0.045	0.30	0.281
Copper	0.0664Ln(C_0) - 0.0488	0.58	0.212
Mercury	0.0767Ln(C_0) + 0.1643	0.52	
Molybdenum	0.0646Ln(C_0) - 0.0152	0.44	
Nickel	0.0987Ln(C_0) - 0.1479	0.44	0.329
Lead	0.0443Ln(C_0) + 0.0171	0.43	0.226
Antimony	0.0763Ln(C_0) - 0.1303	0.31	
Selenium	0.1063Ln(C_0) - 0.062	0.49	
Tin	0.0544Ln(C_0) - 0.0483	0.43	
Vanadium	0.0542Ln(C_0) - 0.1619	0.24	
Zinc	0.0403Ln(C_0) + 0.0561	0.22	0.294
Bromide	0.0383Ln(C_0) + 0.2613	0.41	
Chloride	*0.0298Ln(C_0) + 0.2919*	*0.15*	0.704
Cyanide - total	0.1038Ln(C_0) - 0.1836	0.49	
Cyanide -free	0.1001Ln(C_0) - 0.0099	0.80	
Fluoride	*0.0217Ln(C_0) + 0.1077*	*0.07*	
Sulphate	*0.0166Ln(C_0) + 0.1209*	*0.06*	

Note: The initial concentration (C_0) has units of μg/l

Negative values of kappa are predicted at low initial concentrations for many contaminant species. A negative kappa value suggests that despite the process of flushing, the contaminant concentration in leachate increases with time. This may be because the co-solubility of different contaminants has an effect upon the rate at which they are released from the solid into the leachate with increasing liquid/solid ratio, or there are other reactions occurring in the columns to cause release of the contaminants.

As an example of the magnitude of kappa, Table 6 provides values of kappa for the contaminants listed in Table 4 using the revised most likely concentration for C_0.

3.5 Assessment of the difference between a leachate concentration determined using a constant value for kappa and a concentration dependent value for kappa

Due to the observed relationship between the value of kappa and the contaminant concentration, it was necessary to investigate if the leachate concentration determined using a kappa value which varies depending on the leachate concentration would be significantly different from the leachate concentration determined using a constant kappa value (calculated based on the initial leachate concentration, C_0).

3.5.1   Model construction

The investigation used a model constructed in the GoldSim simulation environment (Section 7.1). The relationship between the value of kappa and leachate concentration was defined in GoldSim using the equations in Table 6. It can be shown that the partition coefficient between solid waste and leachate for a contaminant species is inversely proportional to the value of kappa. The leachate concentration is determined as a result of flushing of contaminants from the waste in which the partition coefficient controls the relative mass of contaminant in the leachate and solid waste phases. A check was put in

place to prevent the calculated partition coefficient becoming negative. This was achieved by preventing a decrease in the value of the partition coefficient during a simulation.

Initial concentrations have been based on LandSim v2 default values (most likely value). For species that do not have default values, the contaminant source concentration is set to the water quality standard value in an attempt to ensure the concentration is of the correct order of magnitude. The contaminants modelled in GoldSim are summarised in Table 6, with the exception of mercury and antimony. These compounds were excluded on the basis that a realistic initial leachate concentration (LandSim default value) produced a negative initial partition coefficient.

3.5.2   Model results and discussion

Results for several key contaminants are presented in Figure 2.

For chloride, the difference between the predicted leachate concentration calculated using a constant and concentration dependent kappa value is negligible (Figure 2). This difference in predicted leachate concentration is also small for fluoride, zinc, lead, molybdenum, cadmium, chromium and sulphate.

Some divergence is observed between the nickel concentration predicted using the constant and concentration dependent value for kappa (Figure 2). The concentration dependent kappa value produces a more rapid fall in concentration. Arsenic, barium, bromide, free cyanide, total cyanide, copper, selenium and tin also exhibit similar behaviour. A constant kappa value tends to predict a higher source (leachate) concentration during the early years of landfill aftercare.

A rapid change in copper concentration is predicted after approximately 1,900 years (Figure 2) followed by a slow reduction in concentration. Arsenic, barium, bromide, free cyanide, total cyanide, molybdenum, cadmium, zinc, tin and selenium also exhibit this behaviour to varying degrees. The effect is due to fixing the calculated partition coefficient for a contaminant at its maximum value to prevent it becoming negative as a result of the calculated small value of kappa.

3.6   Conclusions and recommendations

The kappa driven contaminant specific declining source term should be adopted in LandSim 2.5.

A contaminant specific range of values for kappa could not be identified on the basis of statistical analysis. However, a compelling relationship has been identified from the column test data between initial leachate concentration and the value of kappa.

The results of a simulation of the leachate concentration using both a constant value for kappa (calculated using the initial leachate concentration) and a concentration dependent value for kappa has demonstrated that the difference in predicted concentration is generally small. The leachate concentration calculated using a constant kappa always exceeds that using a concentration dependent kappa value during the early part of the aftercare period, but produces lower concentrations at later times. Given the typically small difference in the two approaches and the additional complexity of the concentration dependent value of kappa it is recommended that value of kappa be calculated based on the initial leachate concentration.

4.0 Simulating the change in concentration of volatile species

4.1 Background

The removal of volatile contaminants via landfill gas results in a declining contaminant source. This was defined by examining the emissions of VOCs in landfill gas from a number of landfills from studies by Knox (1990), Scott et al. (1988a, b), Allen et al. (1997), Young and Parker (1983), Emberton and Scott (1987), and Jones et al. (1988).

Figure 3 indicates the range of VOC concentrations in landfill gas and their decline over a period of up to 30 years. For LandSim 2.5, the work concentrated on whether a similar effect could be seen with leachate concentrations. Should this be the case, this has a material effect on how the source term for the revised LandSim should operate.

There are a number of both synergistic and antagonistic processes controlling the rate of decline of VOCs within a landfill. Firstly, volatilisation from any free product (or neat product sorbed onto material within the site) is largely controlled by the contaminant's vapour pressure (allowing for Raoult's Law where multiple VOCs are present). Secondly, there is the comparable effects of volatilisation directly from leachate (controlled by Henry's Law). Thirdly, there is the effect of partitioning onto organic carbon (controlled by the partition coefficient, K_{oc}). For certain compounds, some degree of biodegradation may also be occurring in the aqueous phase. It is therefore unlikely that a simple relationship exists between the rate of decline of the concentration and any specific physical parameter. Interaction with other species is specifically difficult to determine, as only a limited number of VOCs are typically included in leachate analyses.

4.2 Data collation

Monitoring data from a number of landfills was obtained specifically for volatile organic compounds. The operators who supplied this information have specifically asked that the site details and locations be kept confidential, and their assistance in providing these data is gratefully acknowledged. In some cases these data span periods of over eleven years, although in many cases individual records from specific leachate monitoring wells covered a shorter period.

From the data provided it has been possible to examine four chemical species - toluene, benzene, 1,1 dichloroethane and 1,2 dichloroethane. Each of these species is known to have a relatively high Henry's Law coefficient. There was therefore an expectation that these compounds would preferentially partition into the gas phase within the environment of a gassing landfill and thereby be unavailable to partition into leachate.

4.3 Analyses of collated data

To analyse the change in concentration of VOCs in landfill, the data should be drawn from samples from a specific location (leachate monitoring point) located within a cell that is not receiving any additional waste input. A reasonable monitoring period is needed to ensure that sampling and analytical "noise" is of little or no consequence. Very few monitoring locations were found to meet these requirements, although a number of plots did indicate that there was close agreement with a half-life based declining source term. Where possible, data from individual monitoring points were plotted (concentration against time) for each species. In some cases all of the data from a landfill were plotted together (referred to as "total" on the plots). It has not always been possible to derive an accurate date when waste was originally deposited, so the default time (t=0) was assumed to be the first known monitoring result. This approach may under estimate the original source term, but not the rate constant describing the reduction in concentration. Furthermore, some of the monitoring points were only used for a short period and the precise relationship between all of the points was not determined. It was found that when all the data from a site was plotted on a single graph the value of r^2 (a correlation coefficient calculated using the Pearson formula) was not significant at the P=0.05

level. However, irrespective of this, the trend still showed a downward movement at a rate comparable to the individual leachate monitoring wells.

It is anticipated that the decline in concentration will be a first order exponential decay. In each case a least squares fit to an exponential function was performed, and the exponent derived. Each of the sites were located and operated in such a manner that the infiltration of water to the sites would not result in excessive leaching that could be the cause of the decrease in concentrations observed. One of the sites in particular will have leached no greater than an equivalent liquid/solid ratio of 0.04.

The concentration of compounds on a number of occasions fell below laboratory detection limits. Not all the data had the same detection limits, and in many cases the detection limits changed during the monitoring period. In the majority of cases the detection limits actually increased (i.e. became higher) with early data having detection limits of 1 µg/l and later values reporting a detection limit of 5 µg/l. While it is (to an extent) disappointing that the more recent data had less definition, it is equally important to recognise that the apparent decline in concentration was not simply a function of an improvement in laboratory detection limits. In order to deal numerically with values below the detection limits, values were assumed to be at their detection limit when reported to be below them. This is not the approach normally adopted for developing numerical values of a source term where this is the basis for a probability density function, but it is considered an appropriate means of assessing the concentration decay rates as values calculated will be conservative.

4.4 Results of data analysis

Graphical presentation of the data is presented in Appendix 2. In addition, the decay rate constants are shown in Table 7. It should be noted that the general form of the equation is:

$$C_t = C_o \, e^{-xt}$$

where:

C_t is the concentration at time t

Co is the initial concentration

x is the decay rate give in Table 7 (in days^{-1} if t is in days and years^{-1} if t is in years)

Table 7: Results of back analyses of decay rates for VOCs within leachate

Species \\ Site	Toluene Days (years)	Benzene Days (years)	1,1 Dichloroethane Days (years)	1,2 Dichloroethane Days (years)
A	0.0027 (0.99) 0.0043 (1.6)	0.0003 (0.11)*	0.0023 (0.84) 0.0009 (0.33)*	nd
B	0.0008 (0.29) 0.0005 (0.18) 0.0004 (0.15)*	0.0002 (0.07)* 0.001 (0.37)	0.0006 (0.22) 0.00002 (0.007)*	0.0007 (0.26)
C	0.0002 (0.07)	0.0002 (0.07)	nd	nd
Minimum reliable value	0.0002 (0.07)	0.0002 (0.07)	0.0006 (0.22)	0.0007 (0.26) (based on a sample size of 1)
Equivalent Half-life (y)	10	10	3.2	2.7

* Whilst none of the correlations present in Appendix 2 are significant at the P=0.05 level, these values have been derived from composite groups of sampling locations and are judged less reliable than those values from individual leachate monitoring points.

nd - No (or insufficient) data

In addition to recording the results of the calculation of decay constants, Table 7 also identifies the lowest reliable value for each contaminant assessed (albeit that the value for 1,2 dichloroethane is based on a single data set). It is worth noting that benzene, toluene and 1,1 dichloroethane all have very similar Henry's Law constants (between 0.23 and 0.25) while 1,2 dichloroethane has a much lower value (0.04). There is no evidence to suggest that values derived for the source term decay constants bear any relationship with Henry's Law even though it is assumed that the primary mechanism for the reduction in concentration is volatilisation from leachate into the gas phase. It is possible that the chlorinated solvents are also affected by reductive dehalogenation within the reducing environment of the landfill. This would enhance the apparent reduction in concentration as daughter products are generated. No consistent information on the relative anaerobic biodegradation rates for the two compounds was found, but it is unlikely that a simple relationship between a specific property and the difference in source term decay rates could be conclusively shown with the data set currently available. However, 1,1 dichloroethane is reported to degrade physically via hydrolysis with a half-life of 61 years (Verschueren, 2001). 1,2 dichloroethane has not been reported to degrade via hydrolysis (Drury and Hammons, 1979)).

It is interesting to note that the range of half-lives indicated in the analyses above is not dissimilar to that derived for the half-life of VOCs within landfill gas (4.11 years), albeit that the work quoted in GasSim did not seek to differentiate the different VOC components.

Given various uncertainties in both the process and the values generated some care will be needed in the use of these values. The accepted definition of VOCs is that the Henry's Law coefficient should be greater than 4×10^{-4} (dimensionless) and the molecular weight of the compound should be less than 200 g/mole. The compounds we considered here all had Henry's Law coefficients greater than 4×10^{2} (dimensionless) and molecular weights less than 100 g/mole.

4.5   Recommendations for simulating the change in concentration of volatile compounds

A conservative approach to the definition of the source term for VOCs within landfill leachate needs to be taken until such time that more information becomes available. VOCs are defined as compounds that have a Henry's Law coefficient greater than 4×10^{-4} (dimensionless) and a molecular weight of less than 200 g/mole (Smucker, 1998). A single half-life should be used for all compounds set at the maximum observed value from the data currently available (i.e. ten years).

5.0 Review of literature concerning engineering longevity

This section considers first the longevity of engineered caps and then artificial sealing liners. For each type of engineered cap and artificial sealing liner the literature has been reviewed to identify physical and chemical modes of degradation. Both physical and chemical modes of degradation result in physical increases in the size or rate of occurrence of defects. In the case of dense asphaltic concrete (DAC) basal liners, biological attack has also been considered. The review has distinguished between "degradation of engineering" (an inevitable reduction in performance of the engineered structure) and "failure of engineering" (the reduction in performance of the engineered structure due to poor design, poor choice of materials or poor construction). Failure of engineering is considered outside the scope of this LandSim upgrade.

A separate Environment Agency R&D Project is currently reviewing the long-term performance of flexible membrane liners at landfills taking into account the various failure or degradation mechanisms (P1-500/1 *Assessment of the longterm generation of defects in flexible membrane liners*). Relevant results from this review (due for completion in December 2003) will be incorporated into LandSim in the future, including any new data gathered about the longterm performance of Geosynthetic Clay Liners and Caps.

5.1 Cap longevity

5.1.1 Mineral caps

5.1.1.1 Mechanisms of physical degradation

Review of available literature indicates that clay caps can be vulnerable to desiccation (Daniel, 1995) However this can be mitigated by the rapid placement of cover soils or a membrane (Bonaparte, 1990).

It is recognised that consideration should be given to the potential for desiccation to occur if a drainage layer overlies the clay. There is a likelihood that a cap drainage layer will not be saturated throughout the year and therefore air space could be present above the clay. In addition, the issue of desiccation caused by hot landfill gas from the waste remains unresolved by the literature reviewed. The effect may be mitigated by moisture laden gases. Both these effects are design issues and should not be considered in the context of degradation of engineering.

Freezing and thawing also is stated to be a cause of large increases in hydraulic conductivity (Daniel, 1995) but is not likely to be of concern in the United Kingdom due to the temperate climate.

According to the literature, the main mode of degradation of a clay cap is the development of tensile stress in the landfill cap during waste settlement. Fang (1993) describes waste settlement as having two stages - preliminary settlement through loading followed by secondary settlement through decomposition. According to Fang, the secondary settlement is a result of both biological and physio-chemical processes within the waste.

The settlement process causes degradation of the mineral sealing layer through deformation. The deformation can, according to Jessberger et al (1993), arise either through shearing which does not cause a significant increase in leakage, as it does not result in the development of open cracks, or by cracking when the tensile strength of the clay is exceeded by the stress imposed upon it by the settlement process. Daniel (1995) reports work carried out by Lagatta (1992) who from published data, concluded that most compacted soils cannot withstand tensile strains greater than 0.1 to 1.0% without cracking. Jessberger and Stone (1991) report that Henne (1989) has shown that since the deformation necessary to induce tensile cracking increases with the plasticity of the clay that explains why there is such variability in the strain when cracking occurs. Daniel (1995) summarises research by Murphy and Gilbert (1985) who found that the maximum allowable distortion, Δ/L (where Δ is the vertical settlement distance and L is the horizontal distance over which settlement occurs), was

associated with a tensile strain of 0.1 to 1%, is 0.05 to 0.1. It is concluded therefore that a clay cap requires little distortion before the development of open cracks.

The rate and magnitude of settlement of the waste therefore becomes critical to the rate and the timing of the mineral cap failure. A study of the settlement experienced by a landfill in Meruelo, Northern Spain (Sanchez-Alciturri et al, 1995), shows that the settlement of a 15 m thick waste mass was of the order of 450 mm (3% of the thickness of the waste) over a period of 100-900 days following placement. The study goes on to discuss formulae for settlement rate, stating, importantly, that the rate of settlement decreases with time. The authors summarise work by Sowers (1973) who adopted a behaviour similar to the consolidation of soils in which the settlement rate varies linearly with the logarithm of time; by Yen and Scanlon (1975) who proposed a logarithmic decrease in rate; and by Gandolla (1992) who proposed an exponential decay law. In the UK, Watts and Charles (1990) also consider the settlement of domestic refuse landfill to vary linearly with the logarithm of time. This theory is largely based upon a field study carried out by Cheyney (1983) on an 18 m deep domestic refuse landfill.

Visual inspection of field data confirms the short duration over which most settlement occurs. Landva et al (1984) present graphs of the rate of settlement and total settlement for various types of fill, demonstrating that the majority of settlement has occurred within ten years. The field trial in Meruelo, Northern Spain, which shows a close fit to a log-linear decrease in rate, also demonstrates a rapid reduction in rate of settlement within the first 40 months.

In view of the above data and information it is concluded that the vast majority of settlement has occurred before the end of the typical duration of institutional/operational control of a landfill site. It is assumed that as part of the operation of the site the cap will be maintained at its design infiltration. The literature suggests that following the end of institutional/ operational control any remaining settlement of the waste will not be of sufficient magnitude to compromise the integrity of the cap; enabling a clay cap to maintain its design infiltration indefinitely.

5.1.1.2   *Mechanisms of chemical degradation*

No chemical degradation processes of the cap are described in the literature that was reviewed.

5.1.2   Geosynthetic clay caps

5.1.2.1   *Mechanisms of physical degradation*

Lagatta et al (1997) investigated the hydraulic integrity of Geosynthetic Clay Liner (GCL) when subjected to differential settlement. They reported that overlapped GCL panels maintain their hydraulic integrity when subjected to tensile strains of 1% to 10%, despite in-plane slippage of 25 to 100 mm. One of the main conclusions of the report was that the GCL performs better than compacted clay under differential settlement.

The review of physical degradation of mineral caps has concluded that settlement beyond the period of institutional/operational control will not compromise the integrity of the cap. Given that an overlapped GCL performs better than a compacted clay cap under the tensile strain imposed by differential settlement, then its physical degradation need not be considered further. Since it is considered that the majority of settlement has occurred within the period of institutional/operational control, the GCL cap should preserve its design infiltration throughout the life of the site.

5.1.2.2   *Mechanisms of chemical degradation*

The swell index of the bentonite component of GCL is important in relation to its hydraulic conductivity. The greater the swell index, the more tortuous and complex the route for infiltrating water becomes within the bentonite. As reported by Miles (2002) the majority of naturally occurring bentonites are of the 'low swelling' or 'non swelling' calcium type. Naturally occurring sodium bentonite is less common

but has a far superior swelling index and therefore is more suitable for use in a GCL. In North America natural sodium bentonite (Wyoming bentonite) is most commonly used. As Von Maubeuge, (2002) reports, in other parts of the world, where natural reserves of sodium bentonite are not present, soda ash (Na_2CO_3) is added to calcium bentonite in order to increase the swelling potential. Von Maubeuge states that this 'activated' sodium bentonite tends to degrade more quickly than natural sodium bentonite, and tends to have a higher initial hydraulic conductivity. Von Maubeuge reports upon field testing carried out by Rudolph (1993). Two GCLs were exposed to local North German weather conditions, unconfined, with no free cations available in a cover soil. The results of the test were that the sodium activated bentonite underwent ion exchange within 17 months, whereas the Wyoming bentonite did not show such behaviour after 28 months. The published data for the test shows the activated sodium bentonite to have a swell index that is approximately a quarter of the Wyoming bentonite after the 17 months. The work demonstrates that ion exchange of sodium activated bentonite to calcium bentonite can result in an increase in hydraulic conductivity of GCL.

However, as summarised by Heerten (2002) all sodium (natural and activated) bentonites are susceptible to ion exchange. After ion exchange the remaining sodium bentonite will swell in contact with water and sufficient confining stress and will show self healing properties after desiccation. Even after they have undergone ion exchange, Heerten states that GCLs have better sealing properties than a compacted clay liner under identical conditions.

Heerten (2002) reports that the best performance is obtained by the addition of 4000 g/m^2 to 5000 g/m^2 of natural sodium bentonite as a sealing element. A recently published paper by Mansour (2001) and summarised by Von Maubeuge shows that a natural sodium bentonite GCL single liner when covered by 0.66 m of cover soil remained intact over a five year period. However, the cover soil was calcium poor. The conclusion of the trial was that a GCL can maintain its original properties if designed properly.

Following consideration of the literature it was concluded that if insufficient natural sodium bentonite is added to a GCL, then an increase in infiltration will occur but that this is a design consideration and not degradation of engineering. In addition it is important to note that, as stated by Heerten, GCLs maintain better long term sealing properties than compacted clay liners under identical field conditions. Chemical degradation of GCL caps is therefore not considered to occur.

5.1.3   Flexible membrane caps

5.1.3.1   Mechanisms of physical degradation

Polyethylene liners undergo two types of stress cracking. As described by Reddy and Butul (1999) the first is 'rapid crack' propagation, which is a shattering failure associated with extremely cold temperatures (less than -20ºC). The second is 'slow crack' growth that is initiated by stress combined with a geometrical imperfection.

The extremely low temperatures required for shattering are not likely to occur in the UK. The settlement of the waste has already been identified to primarily occur during the period of institutional/operational control during which time defects in the cap should be repaired. It is believed that the waste settlement necessary to initiate stress cracking is unlikely to occur following the period of institutional/operational control.

In conclusion, there are not any physical processes that lead to the degradation of a flexible membrane cap that should be modelled in LandSim 2.5 (since they are likely to occur during the period of financial provision and should be rectified accordingly).

5.1.3.2   Mechanisms of chemical degradation

According to Hsuan and Koerner et al (1995) degradation can occur chemically within the cap due to oxidation of the polyethylene. Koerner and Daniel (1997) reported three typical stages in the oxidation process:

- the depletion of the antioxidants within the polyethylene;
- the onset of oxidation (induction time) in which no physical properties are lost; and
- polymer degradation through oxidation, during which the polyethylene will deteriorate.

Koerner and Daniel reported durations for each of these three stages following a series of laboratory tests. The simulated tests for a high density polyethylene (HDPE) immersed in constantly moving water (as possibly occurs for surface impoundments) produced a duration of 41 to 44 years at 25ºC for the depletion of antioxidants. A duration of 10 to 30 years was reported for the induction time when there was no change in the physical-mechanical properties. Koerner and Daniel reported the degradation of the HDPE in terms of a half-life (this is the time taken for a specific engineering property to deteriorate by 50%). The half-life was estimated by Koerner and Daniel to be in the region of a few hundred years. The total lifetime for a geosynthetic such as a properly formulated HDPE is therefore considered to be at least a few centuries and possibly one thousand years.

Following a review of the available data it is concluded that oxidation is the main mechanism of chemical degradation of flexible membrane caps.

5.2   Basal liner longevity

Although physical and/or chemical degradation of compacted clay and GCL liners has not been included within LandSim 2.5, it should be noted that these engineered systems may form a less effective barrier to leachate than natural formations (e.g. *in-situ* deposits of low permeability clay). This is due to the unavoidable potential for weaknesses to be introduced during the construction of the engineered barrier amongst other factors. Furthermore the expected increase in the ionic strength of leachates, due to implications of the Landfill Directive, may adversely affect the hydraulic conductivity of GCLs. These factors must be considered when designing and assessing the risks from a proposed landfill liner, particularly for GCLs. Conversely, mineral basal liners may be more effective barriers than *in-situ* deposits of low permeability clay as the fabric of the natural soil is remoulded, removing micro-fissuring. Permeability may also reduce with time due to consolidation and compression of the clay, precipitation of minerals and bioaccumulation. Evidence pertaining to the longevity of mineral liners will remain under review and may be incorporated in future releases of LandSim.

5.2.1   Geomembrane (HDPE) liner

5.2.1.1   Mechanisms of physical degradation

Reddy and Butul (1999) suggested swelling of the HDPE as a possible mechanism by which physical degradation can occur. No further information has been found on swelling and it has not been considered further.

5.2.1.2   Mechanisms of chemical degradation

Reddy and Butul also suggest dissolution by leachate of the HDPE to be a possible degradation mechanism. Overmann et al (1993) have carried out a series of tests on the resistance of HDPE to the chemical environment to which they will be exposed during use. This was carried out through immersion of the material in a landfill leachate in which the immersion temperatures and durations were longer than usually carried out by the United States Environmental Protection Method (1986). The leachate was subjected to immersion temperatures of 23ºC, 45ºC and 70ºC. The exposure times for the geosynthetics were 1, 2, 3, 6, 9, 12, 18 and 24 months. The conclusion of the testing was that the geomembrane will perform adequately with respect to chemical resistance to typical household or co-disposed waste leachates.

Polymer degradation through oxidation of the HDPE is not only considered to occur in a cap but also to a basal liner. Again a three-stage process is considered to apply. Koerner and Daniel (1997) published durations for the antioxidant depletion time for a simulated landfill environment with dry sand below the geomembrane and 300 mm of water above it; a compressive stress was applied. The duration reported was 126 to 128 years at 25ºC. No distinction was made for the oxidation induction

time, or the time to total failure between the HDPE under surface impoundment or basal liner conditions. The oxidation time was therefore assumed to be 10 to 30 years, the degradation half-life to be a few hundred years and the total lifetime to be up to 1,000 years.

5.2.2   Dense asphaltic concrete

5.2.2.1   Mechanisms of physical degradation

The main potential physical damage to a DAC liner is settlement of the sub-grade. According to work carried out in Germany in hydraulic engineering applications, Arand et al (1992), and Haas (1990) DAC liners can accommodate significant amounts of settlement with no reduction in performance. Settlements up to 1:10 have no impact in a hydraulic engineering application, and it is likely that greater settlements can be accommodated in a landfill due to the higher temperature making the DAC liner more ductile.

5.2.2.2   Mechanisms of chemical degradation

Potential chemical damage to a DAC liner comes from organic compounds due to their swelling and solvent actions. When assessing the ability of DAC to withstand chemical attack, the thickness of the liner and type of aggregate material have significant impact on DAC performance. For example, only aggregates that are not water soluble or susceptible to swelling should be used.

Research has shown that asphalt is resistant to extreme leachates – Ryser (1993) reported that asphalt is resistant to a leachate comprising 5 mg/l of AOX (halogenated organic compounds), 45,000 mg/l BOD and 60,000 mg/l COD. Haas (1989 and 1990) claimed that some organic solvents attack the binder in DAC. However, it was suggested by August (1995) that in a landfill application this will not happen since there are insufficient volumes of solvent per square metre, insufficient periods for the solvents to attack and no possibility for the binder to be transported away.

Chemical degradation in the form of ageing may also affect asphalt.

Structural Ageing
Bitumens are colloidal systems. Neumann et al (1992) state that the colloidally dispersed materials in the bitumens are asphaltenes and petroleum resins which form large specific interfaces with a high free interfacial energy. They are reduced by means of particle coarsening until decomposition takes place in two phases with a gain in the free energy. Systems of this type with a high free interfacial energy are not in a state of thermodynamic equilibrium, and therefore have a potential to age. The structural ageing of colloids comprises a change in the composition of the bitumen from a sol to a gel, and this increases the hardness and the strength of the bitumen, with a resulting decrease in plasticity.

Distillation Ageing
Distillation ageing means the evaporation of light hydrocarbons from the malthene phase resulting in an increase in viscosity. Most of the distillation ageing occurs in the short-term production, storage, transportation and installation of the bituminous mixture stage, and very little occurs in the long-term in-use stage.

Oxidative Ageing
The most important ageing mechanism is oxidative ageing. According to Neumann (1987) the oxidative ageing of bitumen with atmospheric oxygen takes place by means of free radical reactions. The free radicals are formed from hydrocarbons due to the action of ultraviolet radiation. However, the reaction starts very slowly and only increases in speed with an increase in the number of free radicals formed. However, if either oxygen or light energy is missing, the conditions for oxidative bitumen ageing are not available. Oxidative ageing produces harder bitumen.

The majority of work on the ageing of bitumen has been carried out for asphalt used in road construction. Road asphalt is typically laid with around 6% air voids, much higher than the 3% used in

DAC construction, and is exposed to oxygen and sunlight for the whole design life. It is considered that the oxidative ageing process in DAC liners will be much slower than within a road, if it occurs at all.

Belling (1992) reports that there is a strong relationship between the voids content of a bitumen binder and its propensity to age, and suggests that ageing is not a problem if the air voids is limited to 3%. A study of 10 to 30 year old asphalt samples by Schönian (1986) found that as the voids content decreases, ageing processes due to oxidative processes slow down but the possibility of their occurring cannot be excluded. He also found that DAC used in hydraulic engineering with a maximum voids content of 3% should last for several decades because the low voids content means that the ultraviolet light and oxygen can only penetrate the top few millimetres in the liner. It follows that a DAC liner used in a landfill environment will last significantly longer due to the absence of ultraviolet light and oxygen for the majority of its lifetime.

Samples taken from an asphalt liner laid in 1935 for a canal in Germany showed that the bitumen binder had undergone oxidation and hardened by 1987, however the liner functioned properly in all other respects (August, 1995).

The ageing resistance of bituminous liners is also considered by Haas (1989) and reference is made to the Babylonians using bituminous liner materials and mortars 5,000 years ago which have yet to completely degrade.

5.2.2.3   Mechanisms of biological degradation

Although bitumen can be subjected to biological attack, the first step in the microbial degradation requires oxygen. Since the landfill will be anaerobic for the majority of the working life of the liner, biological attack on the DAC liner is not considered to be a major issue.

5.2.2.4   Summary of DAC longevity

For the determination of the longevity of a DAC liner, the resistance to physical, chemical and biological attack should be regarded as design issues. It is only the ageing of asphalt that needs to be considered. There is currently information available regarding the ageing of road asphalts and some information on the ageing of DAC used in hydraulic engineering applications. Road asphalts have significantly more voids than the 3% maximum normally used for DAC and therefore the results of research on road asphalts are not directly applicable to DAC.

The majority of research work on the ageing of DAC has been carried out for hydraulic engineering applications. Experience to date suggest that DAC can show signs of ageing after 50 years of service life in a canal with no loss in hydraulic performance. Ageing conditions can be expected to be less aggressive in a landfill environment (no atmospheric oxygen or ultraviolet light exposure), and so the onset of ageing would be expected to be significantly longer. Further, once signs of ageing have been established it is likely that the hydraulic performance of the DAC will remain unaltered for a further unknown timescale.

6.0 The conceptual model for degradation of active measures (engineering and management)

6.1 Degradation of the cap

The conceptual model of how infiltration through either a mineral or FML (flexible membrane liner) cap changes with time is dependent upon the mode and rate by which the sealing properties of the cap change due to its degradation. The conceptual model has therefore been generated based upon the key processes of degradation identified in Section 2. Figure 4 describes this conceptual model of cap performance.

6.1.1 Performance of a mineral and GCL cap

From review of the available literature, no chemical degradation processes have been identified, apart from those that can be mitigated through explicit and documented consideration at the design stage. Physical degradation is expected through settlement of the waste. However, as discussed in Section 2, the majority of settlement was shown to occur within the period of institutional/operational control when repair of the cap will ensure its design properties are maintained.

Several key features however are noted which would modify the rate of infiltration with time, resulting in the conceptual model presented in Figure 4.

The infiltration value is initially high as the waste mass is uncapped.

Following the completion of landfilling, the placement of an engineered mineral or GCL cap and overlying drainage layer reduces infiltration to a low value, which may be specified by the design. However, due to the clogging of the drainage layer, primarily through the processes of siltation, its ability to effectively drain infiltrating rainwater immediately begins to decrease. This results in an increasing head gradient through the cap and a progressive increase in infiltration. Progressive clogging of the drainage layer cap until total failure and the associated increase in head gradient is assumed to result in a linear increase in infiltration from the design value. When the drainage layer is clogged it is inoperable, the head gradient will no longer increase and infiltration will stabilise to a constant rate. Based upon experience of leachate production rates in UK landfills, this infiltration rate is usually taken to be in the order of 30 to 50 mm/year. The reviewed literature does not provide estimates for the total duration over which the cap drainage layer clogs. Golder Associates estimate that the process will occur over two to three decades.

No further changes in infiltration through a mineral cap can occur once the drainage layer has completely degraded.

6.1.2 Performance of a FML cap

The literature review found that specific engineering properties of a FML cap would degrade chemically with time. The main process by which polyethylene (of which a FML is typically composed) is considered to degrade, in the UK, is through oxidation. Figure 4 presents graphically the conceptual model of FML cap performance.

As discussed in Section 3.1.1, high infiltration will occur whilst waste is uncapped. Once the cap is in place, infiltration will reduce to a low value often specified by design. As with a mineral or GCL cap, the process of clogging of the drainage layer will immediately commence, resulting in the inevitable rise in infiltration through defects in the FML. In the absence of literature information, this rise in infiltration is assumed to be linear with time at an identical rate and duration to that of a mineral or GCL cap. As with a mineral or GCL cap, the rate of infiltration will ultimately attain a steady value when the drainage layer is completely clogged (providing the waste has not become completely saturated).

Several simplifications have been applied in order to implement the subsequent process of oxidation of the polyethylene within the conceptual model. The work of Koerner and others (1995, 1997), demonstrated that following the depletion of antioxidants and the incubation period, the degradation of a 'specific engineering property' of the FML will commence. Following the onset of this degradation process it is probable that the degradation will not result in an increase in infiltration immediately. Rather it is assumed that one half-life will pass before the hydraulic properties of the FML deteriorate. Whilst the mode of degradation has been proven experimentally to progress exponentially, it is assumed that this causes a linear increase in infiltration.

The gradient of the linear increase is determined by a fixed 'start point' and 'end point'. The start point is the onset of the second half-life, as discussed above. The end point is the point at which total degradation has occurred, upon which time the infiltration will be limited to that of effective rainfall value through grassland in the vicinity of the landfill. It is intended that the start point and end point values be user defined, however based upon careful consideration of the literature information the following values are proposed.

- for the start point, a value of 250 years is proposed to allow antioxidant depletion, incubation and one half-life to pass;
- for the end point the literature review suggests that total degradation could take 1,000 years. This is the timescale proposed before grassland infiltration occurs (assuming that restoration is to grassland).

Following total cap degradation it is proposed that the grassland infiltration enters the waste indefinitely.

6.2   Degradation of the artificial sealing liner

In LandSim 2.5, the mineral component of a liner is not considered to undergo physical or chemical degradation with time, however the potential for high ionic strength leachates, poor construction or other factors to adversely affect the performance of the mineral component must be explicitly considered at the design stage. The HDPE component of a composite liner will undergo chemical degradation through oxidation in a manner similar to that discussed in Section 5.2.1. The conceptual model adopted for a composite liner is illustrated in Figure 5, which identifies three key stages in the leakage through a composite liner as a function of time.

Leakage through the HDPE component of a composite liner is calculated using an empirical formula based upon the number and the area of defects in the HDPE. In LandSim Version 2 default probability density functions are applied to the number of pinholes, holes and tears and are considered representative over the life of a site, not just post-construction. In practice, the number of defects immediately post construction is likely to be at the lower end of the ranges, but the most likely number of defects will increase with time.

In LandSim 2.5 it is proposed that the most likely number of pinholes, holes and tears increases from the minimum rate of occurrence (immediately post-construction) to the maximum rate of occurrence in the LandSim version 2 range by the time that the onset of oxidation begins. The increase in the number of defects in FML artificial sealing liners should be simulated by selecting the number of defects at each timestep from a probability distribution function. The limits of the distribution should be equivalent to that which is currently in LandSim. However, the most likely value of the distribution should move from the low end of the range to the high end of the range during the period before the FML degrades. The result is that during the period prior to the onset of chemical degradation an increase in leakage will be observed representative of this linear increase in the rate of occurrence of defects.

The linear increase in defect number occurs until the onset of oxidation begins. Experimental data has shown that the oxidation of the polyethylene results in the exponential deterioration of a 'specific engineering property'. Three conceptual models of leakage increase have been proposed to represent this process in terms of the hydraulic properties of the HDPE:

- a doubling of the number of defects over a fixed time period, with the resultant leakage calculated using the Giroud and Bonaparte Equation;
- a doubling of the area of the defects over a fixed time period, with the resultant leakage calculated using the Giroud and Bonaparte Equation;
- a doubling of the rate of leakage over a fixed time period.

Irrespective of the conceptual model for leakage, the increase in the leakage rate, whichever way it is calculated, cannot occur indefinitely. It is ultimately limited by the hydraulic conductivity of the clay component of the liner. As with the approach for FML caps, the onset of oxidation and the degradation rate are intended to be user defined. However, following consideration of the literature, indicative values are provided as follows:

- the onset of degradation is proposed to occur after 150 years, to allow for the depletion of antioxidants, and the induction time to pass;
- the doubling of either the increase in defect number, defect area or leakage over a time period of up to 300 years.

It is therefore proposed to increase leakage due to degradation of an FML on the base before infiltration is increased through an FML used in a cap. This is because the development of a defect (or the increase in area of a pre-existing defect) on the base will immediately result in increased leakage. Infiltration through an FML cap will not significantly increase until a certain degree of degradation of the FML has occurred.

It is proposed that once a rate of leakage equivalent to that through the clay component of the liner is reached that this fixed leakage occurs indefinitely.

6.3   Longevity of institutional/operational control

Whilst an operator or regulator has control of a landfill site it should be able to be maintained according to permit conditions. At some point in the future institutional/operational control may cease if, for instance the operator is no longer in business and the period of financial provision has expired. When this occurs, leachate will no longer be pumped from the waste and it will no longer be treated. Infiltration to waste as a result of leachate recirculation also ends. As a consequence, the leachate head will vary according to a balance of infiltration to the waste from rainfall and leakage through the basal liner. Should the leakage rate always remain lower than the potential infiltration rate, then overtopping (surface discharge) must occur at some point in time.

7.0 Numerical representation of the conceptual model

This section describes how the conceptual model has been converted to a numerical model. A full list of parameters used by the numerical model is provided in Table 8. The table also shows the values assigned to the parameters. The conceptual model is illustrated in Figure 6.

7.1 The simulation environment

The numerical model has been constructed in a simulation environment called 'GoldSim', that was written by Golder Associates. Details of GoldSim are available on the internet at www.goldsim.com.

GoldSim is a graphical simulation environment in which the user can create, document and present models by manipulating graphical objects representing data and the relationships between the data. The Contaminant Transport Module is an extension to GoldSim consisting of specialised elements for representing contaminant species, transport media, transport pathways, contaminant sources and receptors. By linking these elements together (and integrating them with GoldSim's basic elements), the user can build contaminant fate and transport models.

Table 8: List of all parameters used by the model and their values with justification

Contaminants and materials

GoldSim data element	Explanation	Value	Comment
Diffusivity of contaminants in water	Diffusivity of contaminants in water.	1 x 10^{-9} m2/s	
Aquifer water partition coefficients		As =50 l/kg Ba = 2 l/kg Cl = 0 l/kg Cd = 20 l/kg	
Liner water partition coefficients		As =50 l/kg Ba = 2 l/kg Cl = 0 l/kg Cd = 20 l/kg	
Leachate waste partition coefficients		As =33.33 l/kg Ba = 6.67 l/kg Cl = 1.75 l/kg Cd = 2 l/kg	
initial_conc	Initial leachate concentration.	As = 0.00484 mg/l Ba = 10 mg/l Cl = 2270 mg/l Cd = 0.0101 mg/l	Most likely values from LandSim except Ba
kappa	Kappa describes the rate of release from waste into leachate.	As = 0.03 kg/l Ba = 0.15 kg/l Cl = 0.57 kg/l Cd = 1 kg/l	

Geometry

GoldSim data element	Explanation	Value	Comment
cell_width		200 m	
cell_length		200 m	
waste_thickness		20 m	
waste_density		1000 kg/m^3	
waste_porosity		0.4	
waste_field_capacity		0.3	

Timing and institutional control

GoldSim data element	Explanation	Value	Comment
landfilling_duration		10 yr	
duration_institutional_control	Duration of institutional and operational control.	30 yr	The time following landfilling when the cap degrades, leachate is no longer pumped to a treatment plant, leachate recirculation ends and leachate head is therefore no longer fixed.

Cap

GoldSim data element	Explanation	Value	Comment
cap_infiltration	The infiltration to the landfill cap before any degradation occurs.	50 mm/yr	
grassland_infiltration	The infiltration to grassland in the vicinity of the landfill.	140 mm/yr	
time_of_cap_deg_onset	The time since landfilling commenced when FML caps start to degrade.	250 yr	
time_of_total_cap_degradation	The time since landfilling commenced when the degradation of FML caps results in the infiltration being that through grassland in the vicinity of the landfill.	1000 yr	

Hydraulics

GoldSim data element	Explanation	Value	Comment
proposed_permitted_head	The leachate head during operational/institutional control.	1 m	
rainfall_to_waste	Infiltration of rainfall to waste prior to capping.	250 mm/yr	
recirculation_rate	The rate of leachate recirculation.	50 mm/yr	

Liner

GoldSim data element	Explanation	Value	Comment
area_pinhole	The area of a pinhole defect in a FML liner.	2.55 mm^2	Average of LandSim minimum and maximum values.
area_hole	The area of a hole defect in a FML liner.	52.5 mm^2	Average of LandSim minimum and maximum values.
area_tear	The area of a tear defect in a FML liner.	5050 mm^2	Average of LandSim minimum and maximum values.
contact_coefficient	Contact coefficient for calculation of leakage through FML liner.	1.05	Contact coefficient used in LandSim for leakage calculations.
contact_coefficient_r	Contact coefficient for calculation of radius of area of leakage through FML liner.	0.45	Contact coefficient used in LandSim for calculation of radius.
number_pinhole_start	The initial (design) number of pinholes in a FML liner.	0 ha^{-1}	
number_hole_start	The initial (design) number of holes in a FML liner.	0 ha^{-1}	
number-tear_start	The initial (design) number of tears in a FML liner.	0 ha^{-1}	
number_hole_end	The number of holes at the end of the period of institutional control.	5 ha^{-1}	
number_pinhole_end	The number of pinholes at the end of the period.	5 ha^{-1}	
number_tear_end	The number of tears at the end of the period of institutional control.	0.1 ha^{-1}	
clay_permeability	The permeability of the mineral part of a liner.	1 e^{-9} m/s	
mineral_liner_porosity	Porosity of clay liner.	0.3	
mineral_liner_density	Density of clay liner.	1800 kg/m^3	
onset_of_fml_degradation	Time since start of landfilling of the onset of degradation of a FML artificial sealing liner.	150 yrs	
liner_thickness	Thickness of mineral part of liner.	1 m	
degradation_half_life	The rate of degradation of the specified property of a FML artificial sealing liner.	100 yrs	

Saturated Zone

GoldSim data element	Explanation	Value	Comment
thickness_uz	Unsaturated zone thickness.	5 m	
distance_to_receptor_1		10 m	
distance_to_receptor_2		200 m	
darcy_flux	Darcy flux in the saturated zone. The product of hydraulic conductivity and hydraulic gradient.	15 m/yr	
aquifer_porosity	Moisture content of the unsaturated zone and porosity of the saturated zone.	0.3	
aquifer_thickness	Thickness of the saturated zone.	5 m	
aquifer_density	Density of the unsaturated and saturated zone.	2000 kg/m^3	

7.2   Degradation of the cap

The degradation of the cap has undergone some simplification from the conceptual model. Following discussion with the Environment Agency, it was concluded that the degradation of the drainage layer should not be implemented numerically. The value of infiltration to waste therefore changes from effective rainfall on open waste directly to the medium term infiltration following the completion of landfilling. Apart from the removal of this feature, the conceptual model has been implemented precisely as presented in Figure 4 for both a mineral and an FML cap. The change in infiltration through time has been numerically represented using a basic 'selector' element within GoldSim. The selector uses 'if' and 'then' logic to implement the changes in infiltration as the run time elapses.

7.3   Degradation of the artificial sealing liner

The degradation of the composite liner has been implemented numerically precisely as described within the conceptual model, as shown in Figure 5. Basic 'selector' elements have again been used to implement the changes in mode of degradation and leakage rate as the run time elapses.

7.4   Cessation of institutional/operational control

When institutional/operational control ceases, the leachate head may move from its fixed value. The new leachate head is determined from the volume of leachate stored in the waste. This volume is the sum of the volume in the waste when institutional/operational control ended (the field capacity of the waste plus a saturated layer at the base of the waste with a thickness of the permitted head) and a balance of the infiltration of rainfall to the waste and leakage through the liner. Fluxes of leachate off-site, leachate treatment and the rate of leachate recirculation are set to zero once institutional/operational control ends.

8.0 Sensitivity analyses

8.1 Methodology adopted for sensitivity analysis

The sensitivity analyses have been conducted by assessing changes in predictions following alterations to parameters or logic in a base case model. The values of parameters in the base case model are provided in Table 8.

8.2 Sensitivity to values of parameters that define cap degradation

The sensitivity of model predictions to values of parameters that define cap degradation has been explored using a simulation of a composite lined landfill. The artificial sealing liner (FML) is assumed not to degrade and institutional/operational control lasts forever.

8.2.1 Reduced infiltration

Degradation of a FML cap results in changes in infiltration to the waste. Prior to the onset of degradation the infiltration to waste is assumed to be a fixed value. At the onset of degradation infiltration to the waste increases linearly with time. The sensitivity of model predictions to the value of infiltration and timing of the onset of degradation has been tested.

Figure 7 shows the change in predicted chloride concentration in leachate and at the saturated zone receptor if infiltration is reduced from 50 mm/year to 15 mm/year. The leachate concentration at any time is higher with the reduced infiltration because contaminants are not flushed so rapidly from the waste. The effect of this slower reduction in leachate concentration is mirrored in the greater impact on the quality of the groundwater. The peak impact in the saturated zone is greater if infiltration to the waste is reduced.

8.2.2 More rapid onset of cap degradation

The effect of commencing the onset of the cap degradation at 150 years rather than 250 years is shown in Figure 8. The difference in the predicted change in concentration in leachate and in the saturated zone is negligible. This is because the majority of the contamination has been washed from the waste within the first 150 years and the peak impact realised at the water table results from migration of the high strength leachate generated in the early years. A lower concentration of cadmium at the water table can be discerned if the onset of the degradation of the FML cap occurs sooner. This is because the higher infiltration allows a more rapid flush out of cadmium from the waste into leachate that is collected for treatment, and so proportionally more of it is disposed off-site.

8.2.3 Increased infiltration due to more rapid cap degradation

The effect of increasing the rate of infiltration through a FML cap has been simulated by changing the timing of the end of the period of degradation from 1,000 years to 500 years. The results of this sensitivity analysis are presented in Figure 9. The change in chloride peak concentration at a saturated zone receptor is not discernible because the majority of the contamination has been washed from the waste within the first 150 years and the peak impact realised at the water table results from migration of the high strength leachate generated in the early years. The peak impact of cadmium at the water table is less because the increase in infiltration is accelerated by ending the cap degradation at 500 years. The increased infiltration allows a more rapid flush out of cadmium from the waste into leachate that is collected for treatment, and so proportionally more of it is disposed off-site.

8.3 Sensitivity to different concepts of simulating degradation of FML artificial sealing liners

Three different concepts have been proposed that describe the way leakage might increase as an FML degrades. The three concepts have been simulated under the same conditions - no cessation of

institutional/operational control and no cap degradation. The result of the analysis is shown in Figure 10.

The increase in defect number and increase in leakage by the same half life results in the same leakage from the landfill. This is because the calculated leakage rate is directly proportional to the number of defects. It is therefore equivalent if the number of defects or the total leakage is doubled every fixed number of years. Increasing the area of each defect results in leakage increasing much slower because the calculated leakage is proportional to the area of a defect to the power of 0.1. The FML takes approximately ten times as long to completely degrade if the area of a defect is assumed to increase rather than the number of defects increasing.

The lower rate of leakage using the increasing defect area model means the predicted chloride concentration at a receptor in the saturated zone is much less than using the concept of increasing defect number/total leakage rate. However, in our opinion straining the FML following its oxidative degradation is likely to result in existing defects getting larger rather than the generation of more defects.

The predicted travel time to the water table and peak concentration for the three models is distinctly different. Increasing the leakage rate causes the most rapid transport and highest peak impact at the water table. Contaminants travel slowest and have the lowest impact at the water table using the concept of increasing defect number. The result highlights a conceptual difficulty with increasing the leakage rate independently of the Giroud et al (1989a, 1989b) methodology for calculating leakage through FMLs, which is that no account is taken of the increase in wetted area beneath each defect. Under conditions of ever increasing leakage, contaminants are therefore transported through the same wetted area resulting in ever faster contaminant transport to the water table. This is not considered to be realistic in practice.

The calculation of wetted area is more sensitive to an increase in the number of defects than it is to an increase in defect area. Contaminants therefore travel slowest if the number of defects is assumed to increase rather than the area of the defects.

With all three models, slower travel times increase the amount of mechanical dispersion and reduce peak impact.

8.4 Sensitivity to the rate of degradation of FML artificial sealing liners

The sensitivity of predictions to the time over which defect number, defect area or total leakage doubles was studied. The results are shown in Figure 11.

As determined during the analysis of sensitivity of predictions to the conceptual model of leakage, increasing the number of defects and the total leakage has the same effect on predicted leakage rate. By doubling the number of defects every 100 years, the FML has completely degraded after approximately 500 years. Doubling the number of defects every 300 years increases the predicted longevity to approximately 1,400 years.

Doubling the area of defects every 300 years means the leakage rate barely increases between 150 and 1,500 years post landfilling. Doubling the area of defects every 100 years results in leakage more than doubling between 150 and 1,500 years post landfilling.

8.5 Sensitivity to assumed duration of institutional/operational control

An assessment of the duration of institutional/operational control was carried out using a simulation of a clay capped landfill without any degradation of the artificial sealing liner (a composite). The results of the analysis are shown on Figure 12.

The longer institutional/operational control is maintained the longer leachate is discharged off-site from the waste, and the more rapidly is contaminant concentration in leachate reduced. However, the difference in the rate of decrease in leachate concentration is insignificant if control is maintained between 30 and 100 years.

Leakage from the landfill is greater if institutional/operational control is maintained for a shorter period of time because the leachate head is allowed to rise in response to infiltration whilst the number of defects in the FML remains low. As the number of defects increases during the first 150 years, the increased head leads to greater leakage.

The impact at a receptor mirrors the leakage rate - peak impact is slightly higher and occurs quicker if the assumed duration of institutional/operational control is decreased.

8.6   Analysis of ways of controlling numerical oscillations

When institutional/operational control ends, the model stops keeping the leachate head fixed by preventing abstraction from the landfill. The leachate head determines the rate of leakage from the site and this in turn determines the volume of leachate left in the landfill, and thereby the leachate head. This feedback in the calculations can result in numerical oscillations in the solution for leachate head.

The only method that reliably controls the amplitude of the oscillations is reducing the time step length, but this has the knock on effect of increasing run times. The model was run with both degradation of the artificial sealing liner and cap with different time step lengths. In order to prevent the solution for leachate head oscillating under a wide range of conditions of infiltration, degradation and loss of institutional control, the time step duration was reduced to one year.

The prediction of concentration is not dependent on the feedback in the hydraulics calculations. The time step for the concentration calculations should therefore be greater than for the hydraulics calculations to improve run times.

8.7   Analysis of discretisation of unsaturated zone

The model makes use of a Laplace transform to simulate the transport of contaminants along pathways representative of the mineral component of the liner, unsaturated zone and saturated zone. The central concept of the Laplace transform solution technique used by GoldSim (and LandSim) to simulate transport through these pathways is that the discharge history is a linear (and time invariant) function of the input history. Because the Laplace transform approach requires that the transport equations be linear and unchanging in time, if any of the properties of the pathway change during a realisation, the model must use an approximation to represent this change.

In particular, when a change in the properties of a pathway occurs, the change has no effect on mass that was already in the pathway prior to the change. Mass that is already in the pathway continues to be transported based on the properties at the time it entered the pathway. Only mass that enters the pathway subsequent to the change is affected and utilises the updated properties. The approximation can result in errors for pathways that have long contaminant travel times.

In LandSim 2.5, the leakage rate, which determines the rate of contaminant transport through the mineral component of the liner and the unsaturated zone, changes with time. The error in determining contaminant transport for retarded species has to be minimised by discretising the pathway into sub sections. The downside of the sub division is increased run times.

When concentrations are calculated, the error in the contaminant mass transport can be compounded by changes in the flow of water that occur immediately. A large change in the flow of water through the unsaturated zone can therefore lead to the predicted mass being rapidly diluted in too much or too

little water. As a result the predictions show a spike in concentration shortly after the change in flow rate takes place.

Since the flow rate through the liner and unsaturated zone is the same, the errors can be minimised by discretising the length of the pathways. Since typically the unsaturated zone is thicker than the liner, the errors can be minimised by discretising the unsaturated zone.

A comparison of the predictions of a number of simulations after discretising the unsaturated zone into three, five and ten sub sections (known as "pipes" in GoldSim) with the predictions for no discretisation is shown in Figure 13. The simulations have included a degrading FML cap and degrading FML basal liner. The exercise has considered three different durations of institutional/ operational control and three contaminants that behave differently in the landfill and unsaturated zone.

The models with no sub division of the unsaturated zone took approximately 2 minutes to run, and the models with three, five and ten sub divisions took approximately 3 minutes, 5 minutes and 7 minutes to run, respectively.

The predicted concentrations of cadmium, a retarded species, at the base of the unsaturated zone did not exhibit 'noise' because the cadmium did not leave the first pathway subdivision until the flow rate (leakage) had stabilised. For the same reason, the rapid change in flow rates as institutional/operational control ends had no discernible effect on predicted concentrations. Discretisation affects the predicted concentration although the amount of change decreases with increasing number of pathway sub divisions. For instance, the maximum predicted cadmium concentration with five subdivisions is similar to that with ten subdivisions.

The prediction of the concentration of chloride, a rapidly moving contaminant, is 'noisy' during the first 150 years as the leakage rate changes. This is because the volume of water leaving the pipe changes as the leakage rate changes. Increasing the number of sub divisions did not decrease the amplitude of the variations but the amplitude of the variation was small compared with the predicted concentration. The amplitude is kept small because the leakage rate changes gradually minimising the effect of the GoldSim approximation. The rapid increase in flow rate through the unsaturated zone as institutional/operational control ends results in a short lived predicted dilution of chloride at the base of the unsaturated zone. This artificial affect is typically indiscernible at the down gradient monitoring point where compliance in respect of chloride concentration is assessed. Discretising the unsaturated zone into more than three sub sections appears to have little effect on the predicted chloride concentrations.

Toluene is relatively rapidly lost from the source because it is volatile. As a result, the rapid increase in flow rate when institutional/operational control ends only effects the predicted concentration at the base of the unsaturated zone when the period of institutional/operational control is short (40 years in this exercise). Discretisation affects the predicted concentration but, as is the case with cadmium, the change in concentration reduces with increased amounts of pathway subdivision.

8.8   Predictions of the base case model

The base case model has been run with a FML cap and artificial sealing liner. The artificial sealing liner degrades by doubling the area of the defects every 100 years. When institutional/operational control ends, oscillations in the leachate head have been controlled by setting the infiltration equal to 110% leakage when the leachate head rises to 97.5% of the waste thickness.

Figure 14 shows the predictions of the model. Infiltration is high as the waste is uncapped for ten years and falls to a value typical of leachate generation rates observed by landfill operators (50 mm/year). Between 250 and 1,000 years after landfilling commenced the infiltration rises linearly to that of grassland in the vicinity of the site.

Whilst institutional/operational control is maintained (the first 30 years post capping) leachate is disposed off-site. The rate is high to start with as a result of the waste being uncapped but subsequently falls.

The predicted head of leachate rises to a maximum at 100 years from the permitted 1 m once institutional/operational control ends (because infiltration exceeds leakage) but as leakage increases due to the increase in number of defects over the first 150 years of the life of the artificial sealing liner, the head falls to a minimum at 250 years. From 250 years, the leachate head responds to a play off between increasing leakage and increasing infiltration as the cap begins to degrade. The effect of increasing infiltration overrides that of leakage until the cap is fully degraded at 1,000 years. After 1,000 years the leachate head falls in an attempt to achieve a stable level where the leakage is balanced by infiltration.

Since the head of leachate does not exceed the waste thickness, no surface water breakout is predicted in this example.

The predicted leakage from the landfill rises steadily during the period of institutional/operational control as the number of defects in the FML increase. When institutional/operational control is lost after 40 years the rate of leakage increases, as the leachate head rises, peaking at 150 years. The leakage rate then falls, even though the area of leakage is increasing, because the leachate head keeps falling, attempting to reach a level where the predicted leakage (which is a function of the head) equals the infiltration. At 250 years the leakage rate rises, not only because the area of defects is increasing, but also because the head in the landfill increases as infiltration through the degrading cap increases. Whilst not discernible on Figure 14, the leakage rate falls because the head is falling until shortly after 4,000 years when leakage is limited only by the mineral component of the liner and the head stabilises when leakage is balanced by infiltration.

The rate of washout of chloride and cadmium from the waste is initially rapid as infiltration is high. After the initial rapid decreases in leachate concentration, the rate of decrease becomes nearly linear until 1,000 years rather than exponentially decreasing because of the (linear) increasing rate of infiltration through the degrading cap. Once the infiltration stabilises after 1,000 years the rate of decrease of leachate concentration becomes exponentially decreasing.

Peak impact of cadmium at the water table is a response to the initial high leachate concentration. The highest chloride concentration in the saturated zone is a response to the initial high leachate concentration. A secondary peak occurs in response to the more stable leachate concentrations that are predicted following the cessation of institutional/operational control when the leakage rate remains low (and contaminants are therefore not flushed from the waste).

The results presented in Figure 7 are for a landfill where the artificial sealing liner does not degrade and institutional/operational control lasts forever. The effect of the degradation of the artificial sealing liner and the end of institutional/operational control can be assessed by comparing the prediction of chloride concentration at the saturated zone receptor in Figure 14 with the results in Figure 7. The peak impact of chloride at the saturated zone receptor is approximately twenty times greater when the artificial sealing liner degrades and institutional/operational control ends. However, degradation of the artificial sealing liner is not considered to be significantly affecting the predicted peak chloride concentration. The difference is attributable to the rise in leachate head following the ending of institutional/operational control and the consequent increase in leakage.

The difference in the peak impact of cadmium at the water table can be assessed by comparing Figure 8 or Figure 9 and Figure 14. The difference in peak cadmium concentration is negligible. This is because the peak concentration of cadmium is determined by the amount of retardation and dispersion of the leachate in the mineral component of the landfill liner, and the unsaturated zone during the early part of the landfill's life when the leachate strength is highest. The strength of leachate in the early part of the landfill's life is not affected by the duration of operational/institutional control.

Figure 15 shows the effect of extending the period of operational/institutional control to 400 years. The predicted peak cadmium concentration at the base of the unsaturated zone and peak chloride concentration at the saturated zone receptor is reduced by a factor of approximately two by extending the duration of operational/institutional control. It is apparent from Figure 14 and Figure 15 that the predicted peak concentration is a function of the leachate concentration when operational/institutional control ends.

This sensitivity analysis has not assessed the impact of ammonium or other inorganic and organic contaminants. While the modelled 'impact' of this theoretical site appears marginal with respect to chloride and cadmium, it seems highly probable that there would be a wholly unacceptable impact from ammoniacal nitrogen if current acceptance criteria were used. If ammoniacal nitrogen is not flushed from the waste whilst there is operational/institutional control, then the predicted performance of landfill is unlikely to be satisfactory. The proposed means of simulation of the ending of operational/institutional control is likely to result in the extension of the periods of financial provision combined with the need to treat and then recirculate leachate at relatively high rates.

9.0 Other changes to Landsim for version 2.5

It is proposed to make a number of more minor changes for LandSim v2.5 and these are described in this section.

9.1 Correlation of saturated zone hydraulic conductivity and hydraulic gradient

Selected values of saturated zone hydraulic conductivity and hydraulic gradient by LandSim v2 are independent of one another. However, whilst a user may have order of magnitude uncertainty in the value of hydraulic conductivity and hydraulic gradient, the magnitude of Darcy flux (the product of hydraulic conductivity and hydraulic gradient) is usually understood with greater certainty in the case of a well characterised landfill, because it can be compared with the amount of recharge up gradient of the site. LandSim can select a low value of hydraulic conductivity and a low value of hydraulic gradient when in reality low hydraulic conductivity usually causes high hydraulic gradient. The current approach of encouraging users to express their uncertainty in hydraulic conductivity and hydraulic gradient independently, combined with the lack of correlation of these values, results in an unnecessarily large range in calculated underflows and thereby over and under predicts concentration at extreme percentiles.

It is therefore proposed to give the user the option of entering hydraulic conductivity and hydraulic gradient as at present, or Darcy flux and uncertainty in its value, instead.

9.2 Simulation of flow in the landfill liner

Engineered basal liners act only to limit the amount of leakage of leachate to the unsaturated zone in LandSim v2. It is proposed to modify the model to allow simulation of geochemical processes of advection, dispersion, partition and biodegradation in the wetted mineral part of basal lining systems. The wetted area should be determined in the same way as the wetted area of the unsaturated zone is calculated using the approach of Giroud and Bonaparte (1989a and 1989b), and Giroud et al (1992). The proposed change will permit more realistic calculation of contaminant transport times and concentration at compliance points.

9.3 Removal of cation exchange capacity

LandSim 2.02 compares the cation exchange capacity of the mineral component of the basal liner and unsaturated zone with the mass of ammoniacal nitrogen that is predicted to leak from the liner, if the model is run in unretarded mode. The cation exchange capacity is used to delay the impact of ammoniacal nitrogen at the water table. The approach implicitly assumes that the process of cation exchange is irreversible whereas laboratory experiments and experience from the field suggests sorbed species are remobilised when lower strength leachate moves through the material. This reversible aspect to the process is not represented in LandSim 2.02.

The introduction of more realism into LandSim 2.5 has meant that it has been necessary to remove the sorption option from the model and instead it is considered more reasonable to simulate attenuation in the unsaturated zone using equilibrium partition described by a partition coefficient, K_D. Users should be aware that determination of the cation exchange capacity of geological material at landfills may still be useful since methods exist for calculating a partition coefficient (K_D) from the cation exchange capacity. Such a method is presented in Environment Agency (2002).

10.0 Conclusions of the scoping study

10.1 Simulating the leachate source

Overestimation of the initial concentration of leachate species not on List I can be minimised by using data representative of average leachate quality. Data have been collected from landfills where both spot measurements of leachate quality and measurements of bulk leachate quality exist. Probability density functions of the spot measurements were sampled a number of times and the values averaged. Once the spot measurements were sampled approximately seven times and averaged, the resulting distribution is sufficiently close to the distribution of bulk leachate quality data even at extreme percentiles.

A species specific means of simulating the change in concentration of non-volatile organic compounds was recently presented at the EU Technical Adaptation Committee dealing with the Landfill Directive. The rate of change of concentration is determined by a species specific kappa value. Over two thousand kappa values for different species in different waste types were collated. Analysis of the data found that a single kappa range could not be established for each species, which would adequately represent all types of waste. A strong correlation was identified between the initial concentration of a species in leachate and the value of kappa. The results of a simulation of leachate concentration using both a constant value for kappa (calculated using the initial leachate concentration) and a concentration dependent value for kappa demonstrated that the difference in predicted concentration is generally small.

The removal of volatile compounds via landfill gas results in a declining concentration in the gas and leachate phases. Data describing the concentration of four volatile organic compounds in leachate was collected. Analysis of the data suggested the reduction in concentration is exponential with a half life of less than ten years.

10.2 Simulating engineering longevity and active controls

A brief review of literature was carried out to identify physical and chemical processes that would result in the degradation of engineered landfill caps and basal liners.

It is assumed that any reduction in cap performance would be repaired during the period of institutional/operational control and that degradation processes, if they occurred, would only result in an increase in infiltration of rainfall to waste after this period has elapsed. There were not any processes identified that would result in the degradation of mineral and GCL caps; subject to explicit consideration of potential adverse performance due to leachate chemistry, construction or other factors at the design stage. Oxidation of FML caps would result in an increase in infiltration that, in the absence of other indications, is assumed to be linear.

Two types of artificial sealing liners were considered - FMLs and DAC. The literature suggested that FMLs degrade by oxidation that results in the exponential reduction of engineered performance. The information presently available suggested that DAC would be likely to be robust in the landfill environment. It is likely that DAC would eventually degrade by oxidative ageing but there was no information in the literature reviewed to quantify its longevity.

A numerical model was constructed to simulate the degradation of landfill caps and artificial sealing liners, and the cessation of institutional/operational control. An analysis of the sensitivity of the predicted groundwater quality to choices of conceptual model and parameter value was carried out.

The sensitivity analysis established:

- the value of infiltration to the waste post capping is important in determining impact at the water table. The peak impact in the saturated zone is greater if infiltration to the waste is reduced;

- the onset and end point of cap degradation do not significantly affect predictions of the model;

- the conceptual model of doubling leakage rate through a FML over a fixed period of time is not internally consistent because the wetted area of the mineral part of the liner is not increased. The concept of increasing leakage rate by increasing the area of defects results in a slower increase in leakage rate than by increasing the number of defects. The effect of both models in terms of peak concentration in the base of the unsaturated zone and at a saturated zone receptor is similar;

- the conceptual model of increasing leakage rate through a FML by increasing the area of defects is sensitive to reducing the time period over which the area of defects doubles;

- predicted concentrations of contaminants are not particularly sensitive to the assumed duration of institutional/operational control;

- the most efficient of the ways of controlling the numerical oscillations that occur when the waste becomes saturated is to set the time step for hydraulics calculations to one year;

- the errors introduced in changing flow rates through the liner and unsaturated zone pathways can be minimised by discretising the unsaturated pathway.

10.3   Other changes to Landsim

Overly conservative predictions of concentrations at extreme percentiles can be minimised by allowing the user to express uncertainty in Darcy flux instead of saturated zone hydraulic conductivity and hydraulic gradient.

Including processes of advection, dispersion, partition and biodegradation in the wetted mineral part of basal lining systems would permit more realistic calculation of contaminant transport times and concentration at compliance points.

The introduction of greater realism to LandSim 2.5 means that the process of irreversible cation exchange should be removed from the model.

11.0 Recommendations of the study

11.1 Simulating the leachate source

It is recommended that the dialogue box describing the leachate source be modified to include a tick box for species not on List I, so a user can identify whether the range of concentration relates to spot measurements of leachate quality or bulk leachate quality. Where spot measurements of leachate quality are input, the initial concentration of species not on List I, should be calculated from the average of at least seven values sampled from the distribution.

The way in which the concentration of species changes with time should depend on the volatility of the species.

It is recommended that the change in concentration of non-volatile species should be determined using species specific kappa values. The kappa values should be calculated using the initial concentration of each species in leachate and remain constant throughout a simulation.

The concentration of volatile organic species (those with a Henry's Law coefficient greater than $4x10^{-4}$ (dimensionless) and a molecular weight of less than 200 g/moles) should reduce with a half-life of ten years.

11.2 Simulating engineering longevity and active controls

On the basis of the literature review and sensitivity study presented in this document the following is recommended for the development of LandSim 2.5.

- the degradation of mineral and GCL caps should not be simulated;

- the degradation of FML caps should be simulated with a linear increase in infiltration between start and end times;

- the degradation of FML artificial sealing liners should be simulated by increasing the area of existing defects using a half life;

- the number of defects in FML artificial sealing liners should be increased from the time of construction until the onset of degradation. The increase in the number of defects in FML artificial sealing liners should be simulated by selecting the number of defects at each timestep from a probability distribution function. The limits of the distribution should be equivalent to that which is currently in LandSim. However, the most likely value of the distribution should move from the low end of the range to the high end of the range during the period before the FML degrades, i.e. immediately after construction the probability density function for the rate of occurrence of pinholes will have a minimum of 0/ha, a most likely of 0/ha and a maximum of 25/ha, whereas after 150 years it will have a minimum of 0/ha, a most likely of 25/ha and a maximum of 25/ha;

- the degradation of DAC should not be simulated;

- the ending of institutional/operational control should result in the leachate head varying according to a balance of inflow of water and leakage of leachate from the landfill;

- the oscillations in leachate head should be controlled by setting the time step used for hydraulics calculations to one year. Larger time steps should be used for calculation of contaminant migration to prevent run times becoming excessive;

- the pathway representing the unsaturated zone should discretised into five sections.

On the basis of current knowledge (and subject to the results of ongoing and future R&D), it is suggested that the default values (which may be changed by the user if alternative evidence is available) are:

- for the start time of FML cap degradation to be 250 years and the end point 1,000 years;

- since degradation of basal liners will have an immediate effect on leakage, that FML artificial sealing liners should begin to degrade after 150 years. The time period over which the area of defects doubles should be 100 years.

11.3 Other changes to LandSim

The user should be given the option of expressing uncertainty in Darcy flux instead of saturated zone hydraulic conductivity and hydraulic gradient.

Simulation of geochemical processes of advection, dispersion, partition and biodegradation should be enabled in the wetted mineral part of basal lining systems.

LandSim 2.5 should not permit simulation of irreversible sorption.

11.4 Acknowledgements

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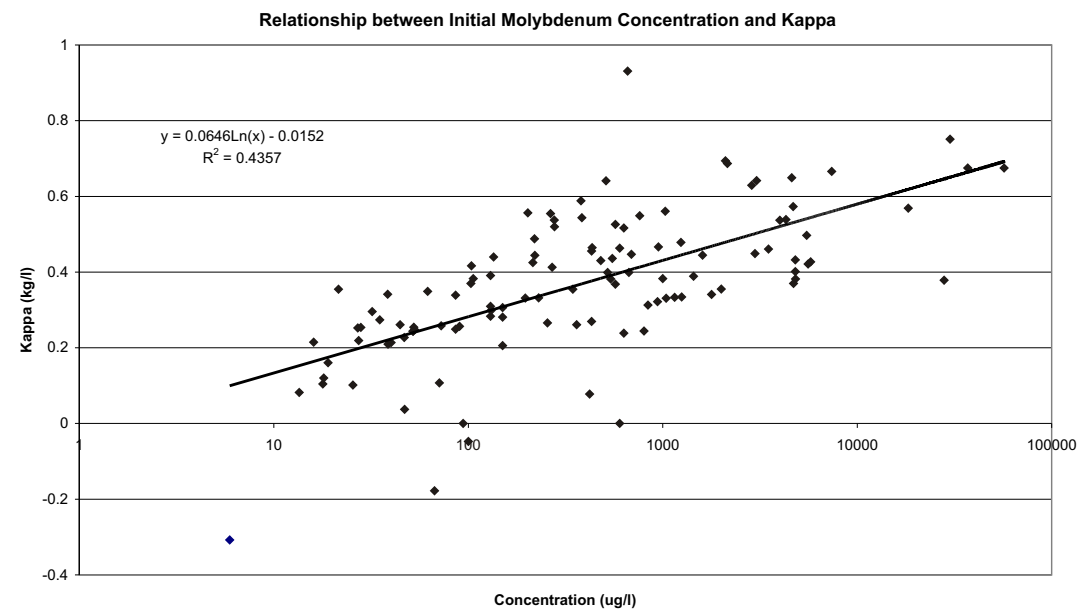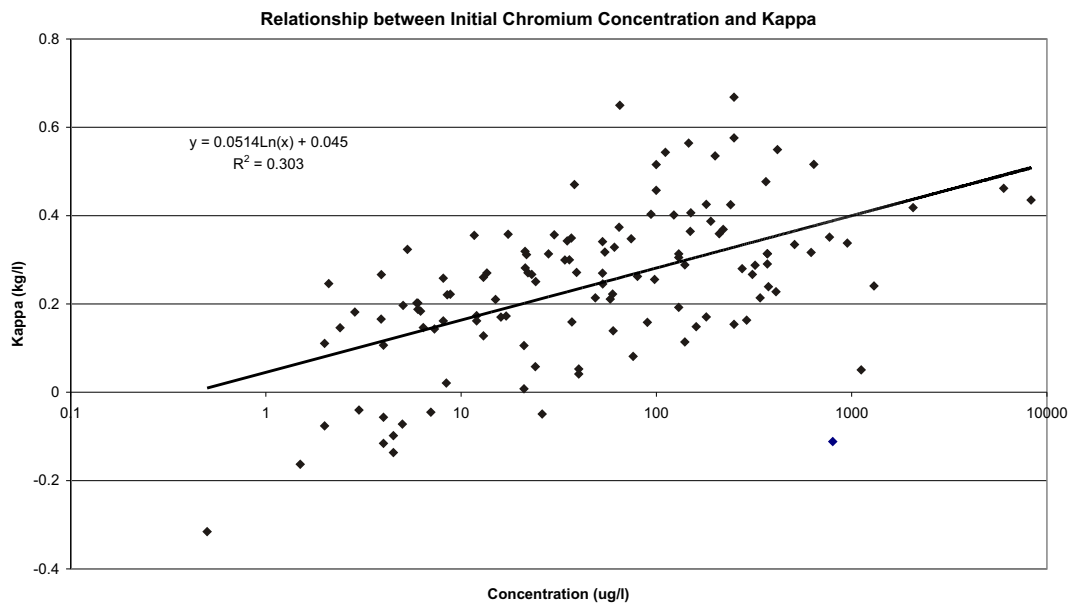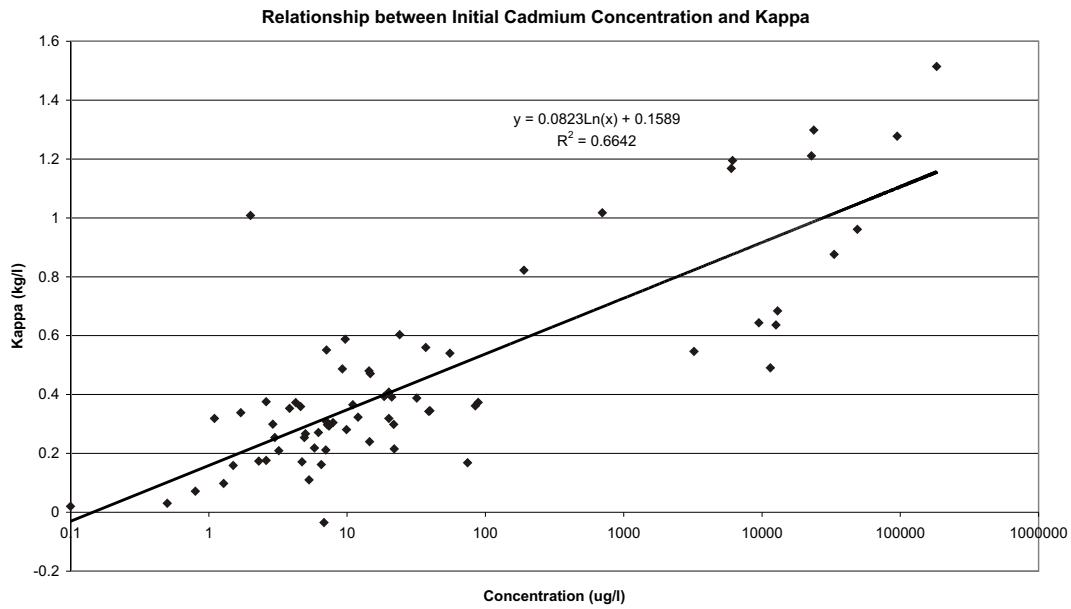
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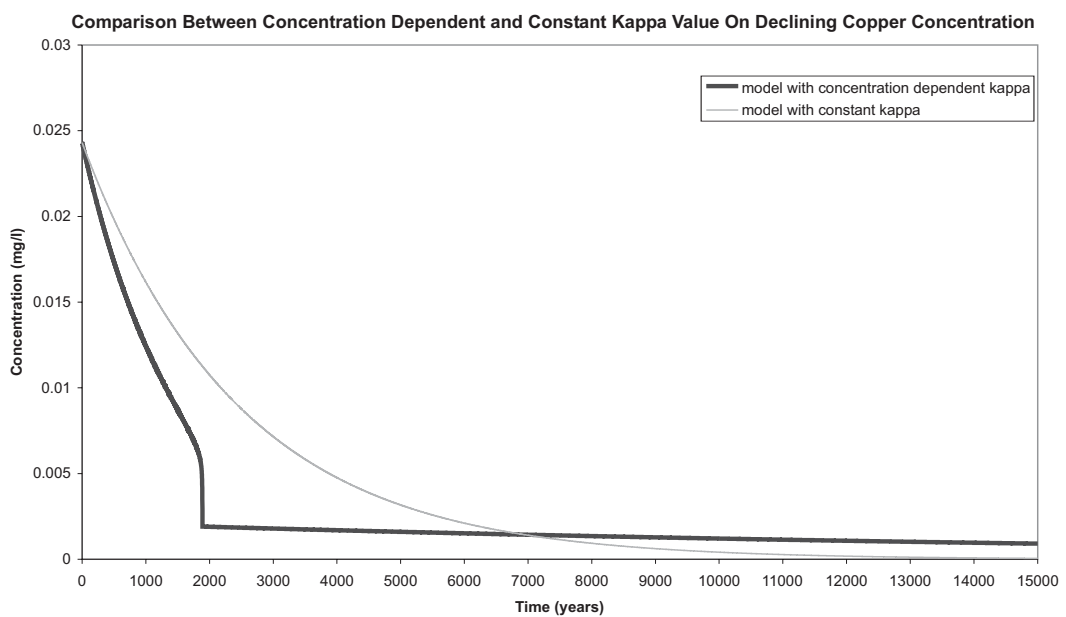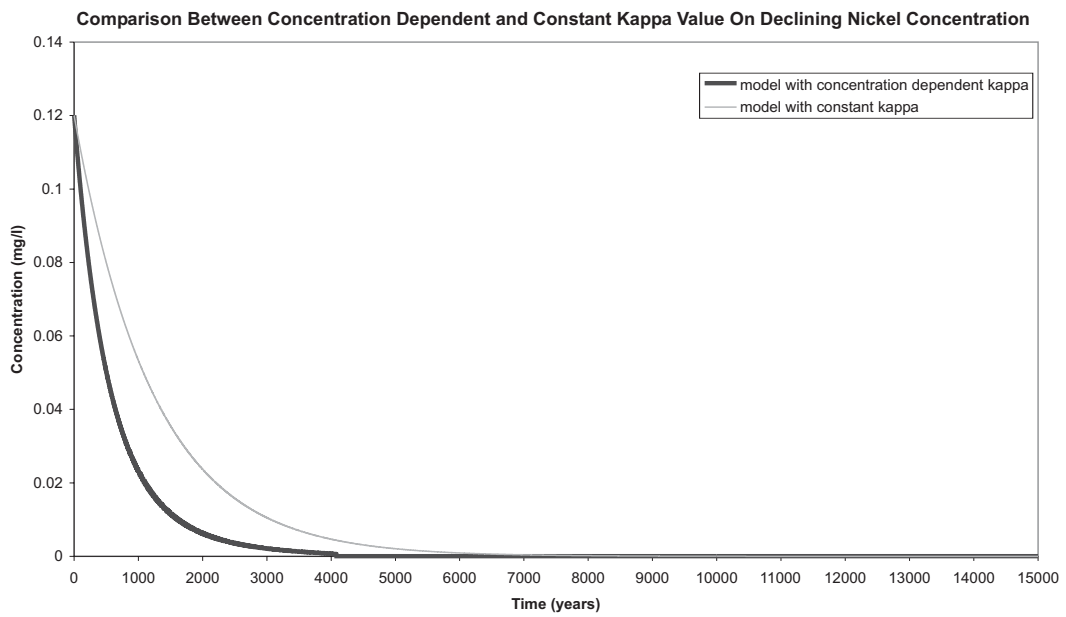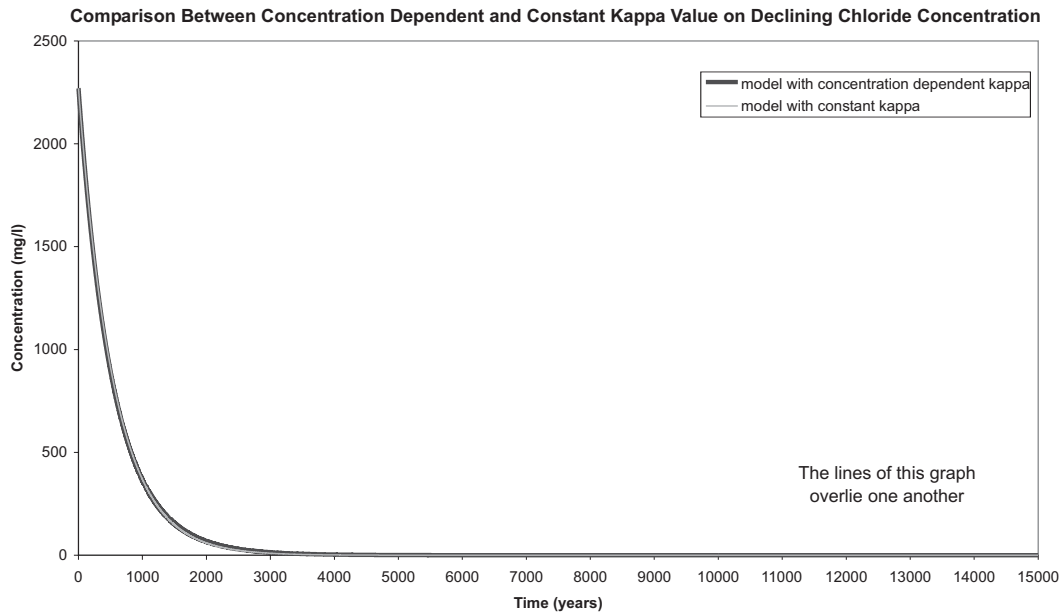
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Figures

Relationship between Initial Cadmium Concentration and Kappa

$y = 0.0823\text{Ln}(x) + 0.1589$
$R^2 = 0.6642$

Kappa (kg/l)

Concentration (ug/l)

Relationship between Initial Chromium Concentration and Kappa

$y = 0.0514\text{Ln}(x) + 0.045$
$R^2 = 0.303$

Kappa (kg/l)

Concentration (ug/l)

Relationship between Initial Molybdenum Concentration and Kappa

$y = 0.0646\text{Ln}(x) - 0.0152$
$R^2 = 0.4357$

Kappa (kg/l)

Concentration (ug/l)

Date	01/09/03	*Title*	
Project No.	02523429	***Relationship between initial contaminant concentration and value of kappa***	**Figure**
Created by	C.W.		**1**
File No.	5219813r1		

Comparison Between Concentration Dependent and Constant Kappa Value on Declining Chloride Concentration

The lines of this graph overlie one another

Comparison Between Concentration Dependent and Constant Kappa Value On Declining Nickel Concentration

Comparison Between Concentration Dependent and Constant Kappa Value On Declining Copper Concentration

Date	14/02/03	Title	Figure
Project No.	02523429	*Difference between leachate concentration determined using a constant value for kappa and a concentration dependent value for kappa*	**2**
Created by	C.W.		
File No.	5219814r1		

Total trace components as a function of average landfill age

Genstat fitted curve
$y = 3067 \,(\pm\, 452)\, e^{-(0.1685 \,\pm\, 0.0639)\, t}$
$R^2 = 0.23$
$t_{1/2} = 4.11 \pm 1.56$ years

Legend:
- ◇ observed data
- —— Genstat fitted curve
- - - - 95% CI
- - - - -95% CI

X-axis: times (years)
Y-axis: total VOCs (mg/m3)
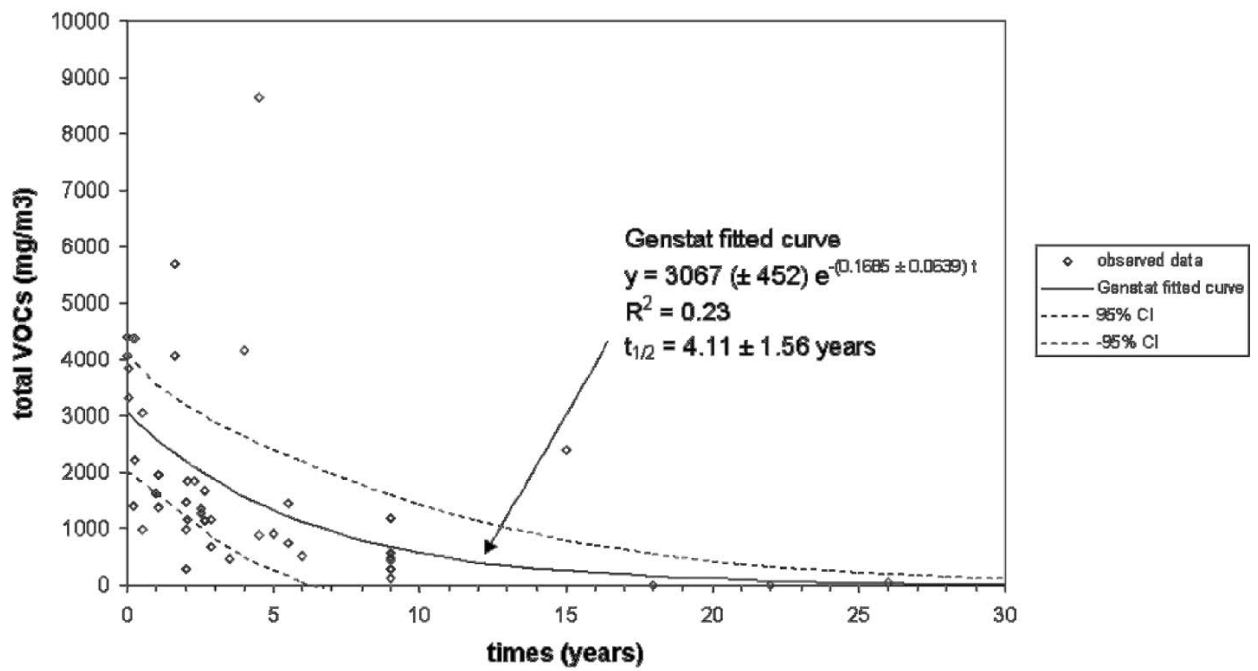
Date	07/10/03	Title	Figure
Project No.	02523429	**Total trace components in landfill gas as a function of average landfill age(Environment Agency, 2002).**	**3**
Created by	C.W.		
File No.	5220787		

Figure 4: Conceptual model of degradation of the capping layer and resulting increase in infiltration to waste

Chart labels:
- Waste open - high infiltration
- Cap design infiltration
- Cap drainage layer fails- head in cap increases
- Antioxidants are exhausted and induction time passed - infiltration increases as PE degrades
- Infiltration to grassland
- No chemical or physical degradation of mineral and GCL capping layers
- infiltration - PE caps
- infiltration - mineral and GCL caps
- Infiltration (y-axis)
- Suggested timescale (years) (x-axis)

Date	07/01/03	Title	Figure
Project No.	02523429	Conceptual model of degradation of the capping layer and resulting increase in infiltration to waste	4
Created by	C.W.		
File No.	5219549r1		

Conceptual model of degradation of the artificial sealing liner and resulting increase in leakage

Date	07/01/03	Title	Figure
Project No.	02523429	**Conceptual model of degradation of the artificial sealing liner and resulting increase in leakage**	
Created by	C.W.		**5**
File No.	5219550r1		

Leakage rate

Suggested timescale (years)

leakage from HDPE liners

Leakage limited to that through mineral

Leakage increases in a non linear fashion as the area of defects double every few hundred years

Antioxidants depleted and induction time passed.

Initial defect distribution

Increase in defect distribution as most likely number of defects increases.

Infiltration through an FML
cap increases after 250 years

Recirculated leachate (so long
as leachate is being treated)

Surface water breakout

Waste

Leachate concentration
varies according to
$C = C_o e^{-kLS}$

Flow to leachate
treatment plant (so
long as leachate
is being treated)

Leachate head is fixed during
period of institutional/operational
control, then allowed to vary

leakage

Basal liner degrades with a
half-life increase in the area
of defects in the HDPE
component after 150 years

Saturated zone receptor -
compliance point for
List II species

Water table - compliance
point for species to be
treated as List I

Date	14/02/03	Title *Illustration of the Conceptual Model*	*Figure*
Project No.	02523429		
Created by	C.W.		**6**
File No.	5219881		

Concentration of Chloride in Waste

Concentration of Chloride at Saturated Zone Receptor
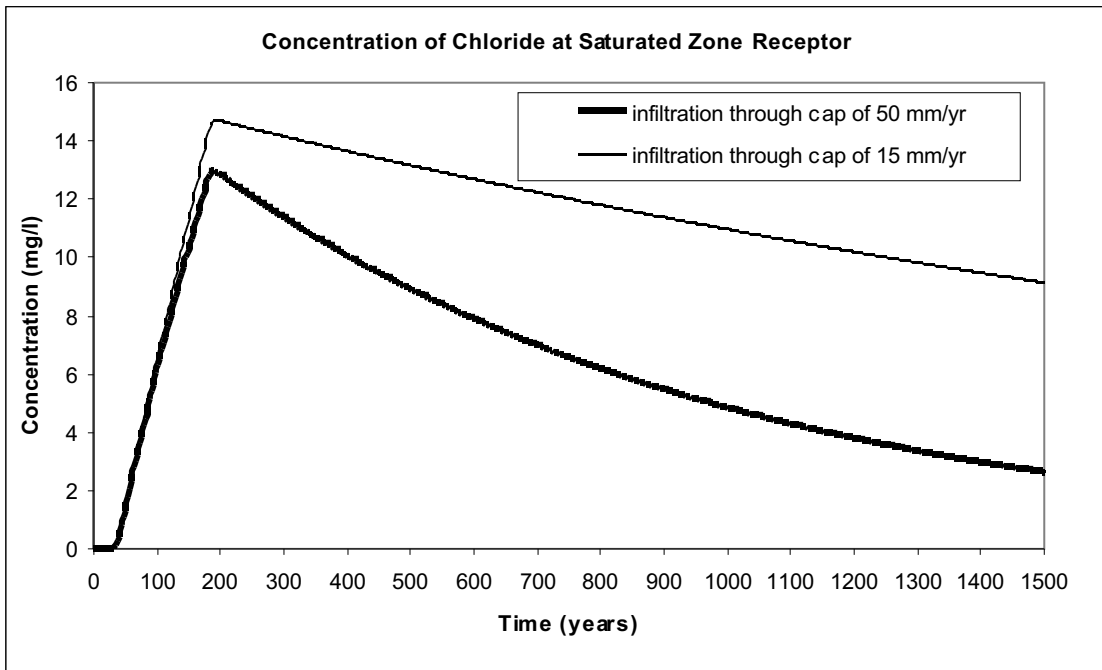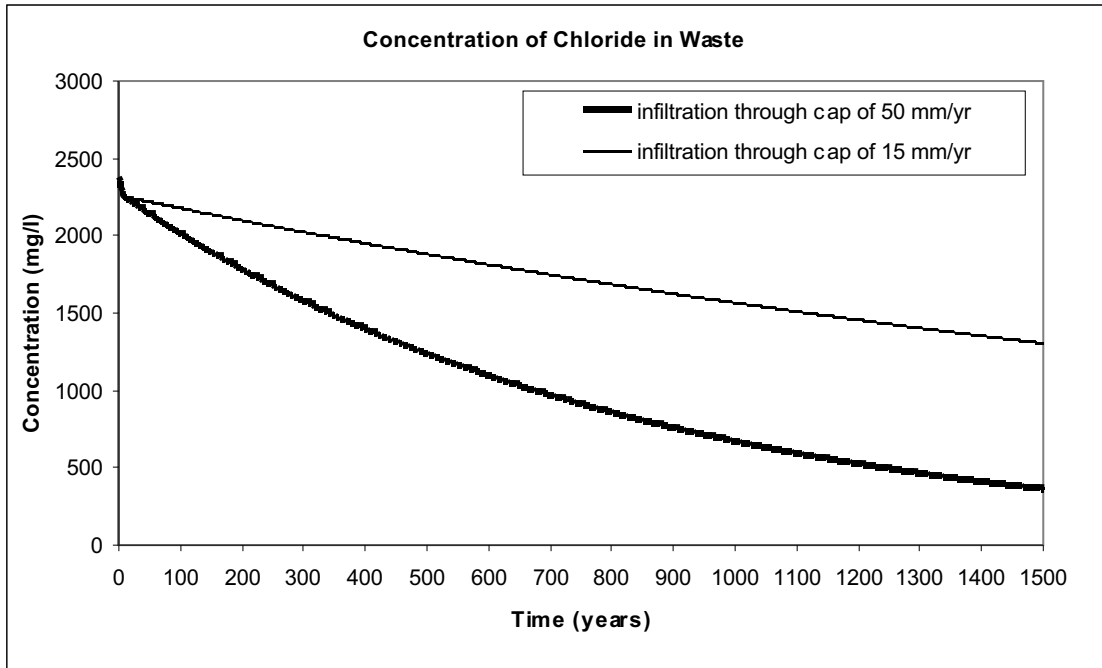
Date	14/02/03	*Title*	**Figure**
Project No.	02523429	***Analysis of sensitivity of predictions to the infiltration to waste***	
Created by	C.W.		**7**
File No.	5219551r2		

Concentration of Chloride in Waste

The lines of this graph overlie one another

Concentration of Chloride at the Saturated Zone Receptor

The lines of this graph overlie one another

Concentration of Cadmium in Waste

The lines of this graph overlie one another

Concentration of Cadmium at the Base of the Unsaturated Zone
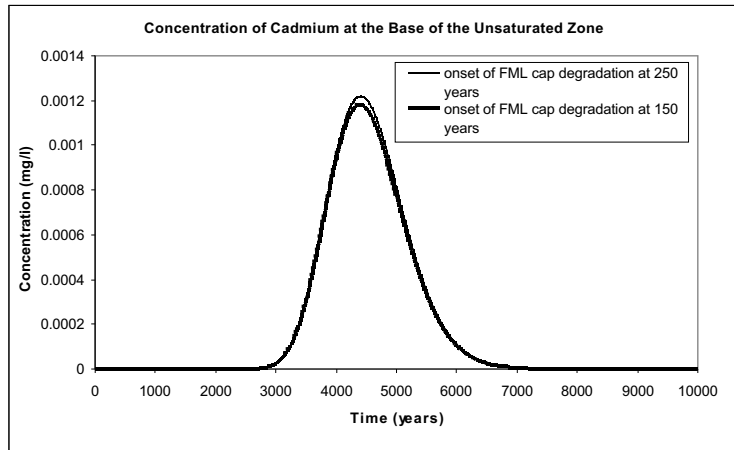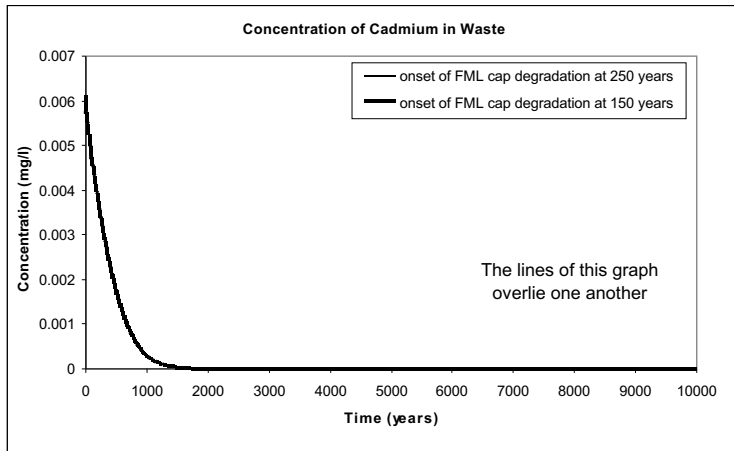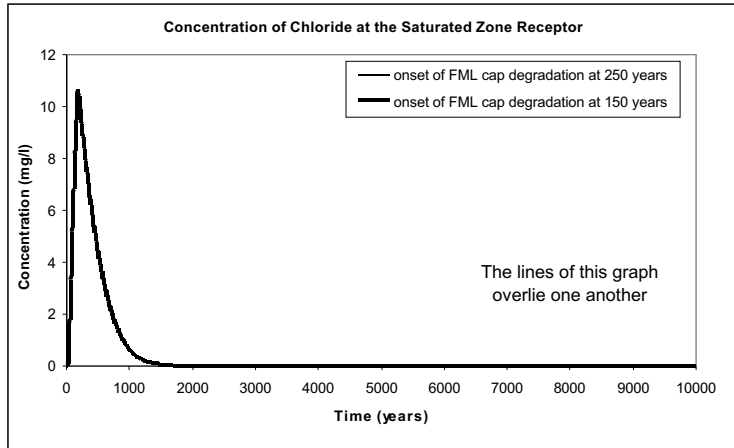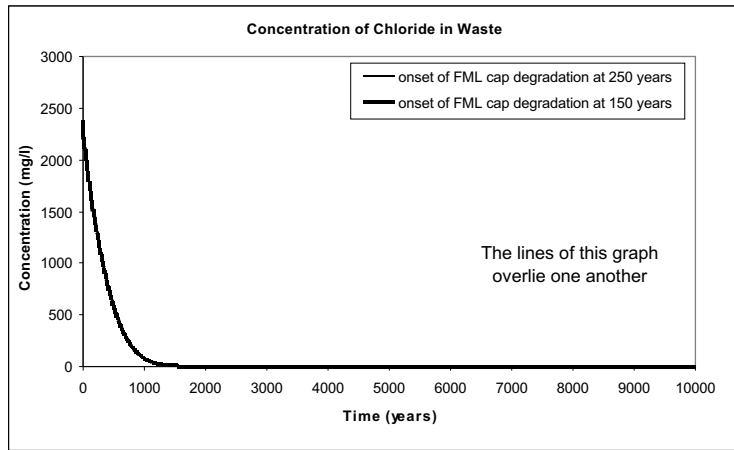
Date	14/02/03	Title	Figure
Project No.	02523429	***Sensitivity of predictions to different times of the onset of degradation of FML caps***	**8**
Created by	C.W.		
File No.	5219552r2		

Concentration of Chloride in Waste

Concentration of Chloride at the Saturated Zone Receptor

Concentration of Cadmium in Waste

Concentration of Cadmium at the Base of the Unsaturated Zone
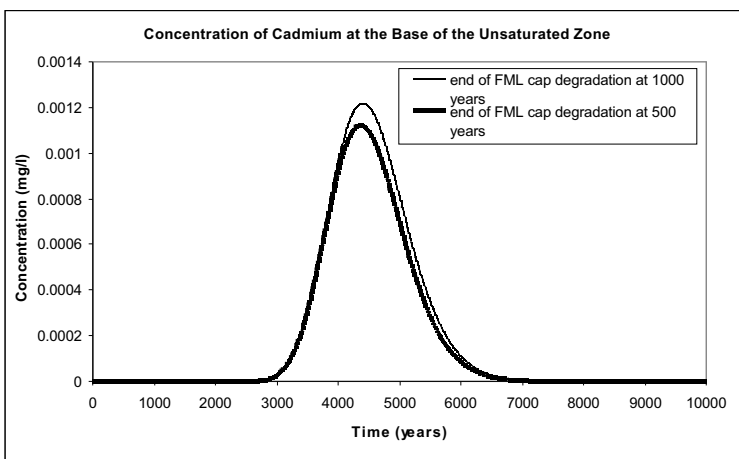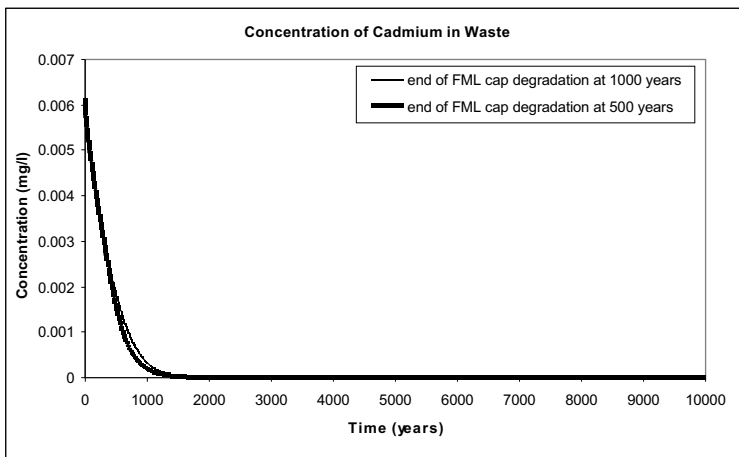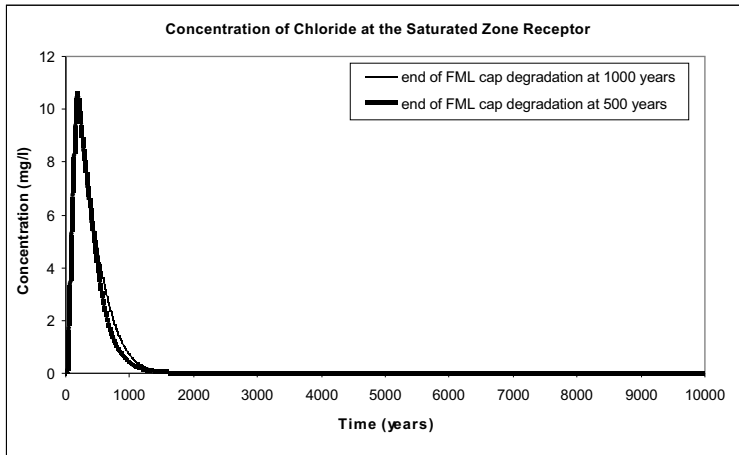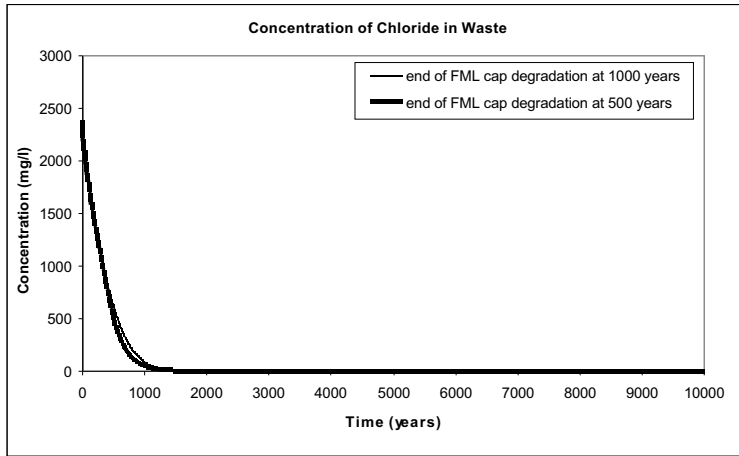
Date	14/02/03	*Title* **Sensitivity of predictions to different times of the end of degradation of FML caps**	*Figure* **9**
Project No.	02523429		
Created by	C.W.		
File No.	5219553r2		
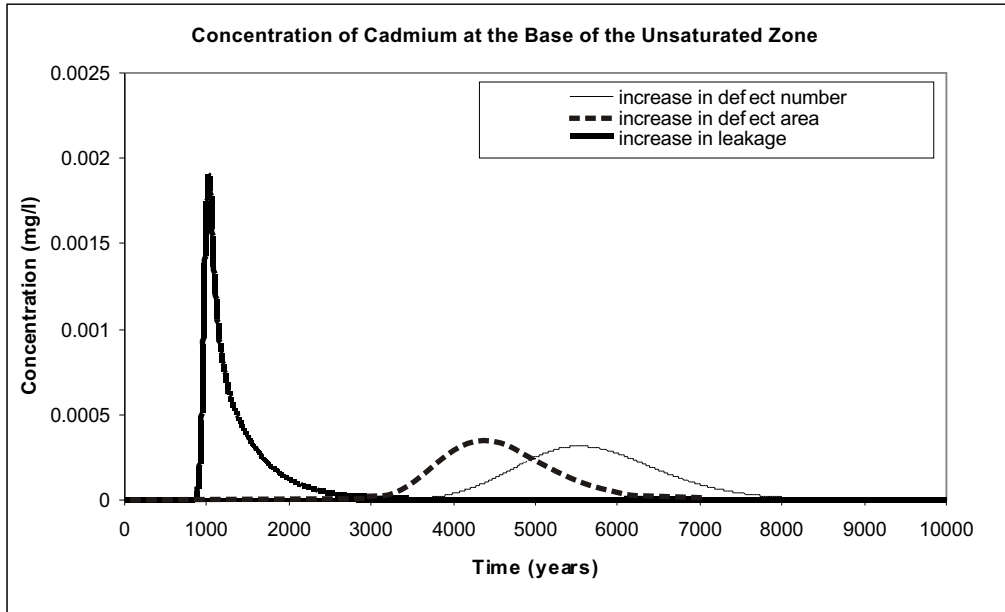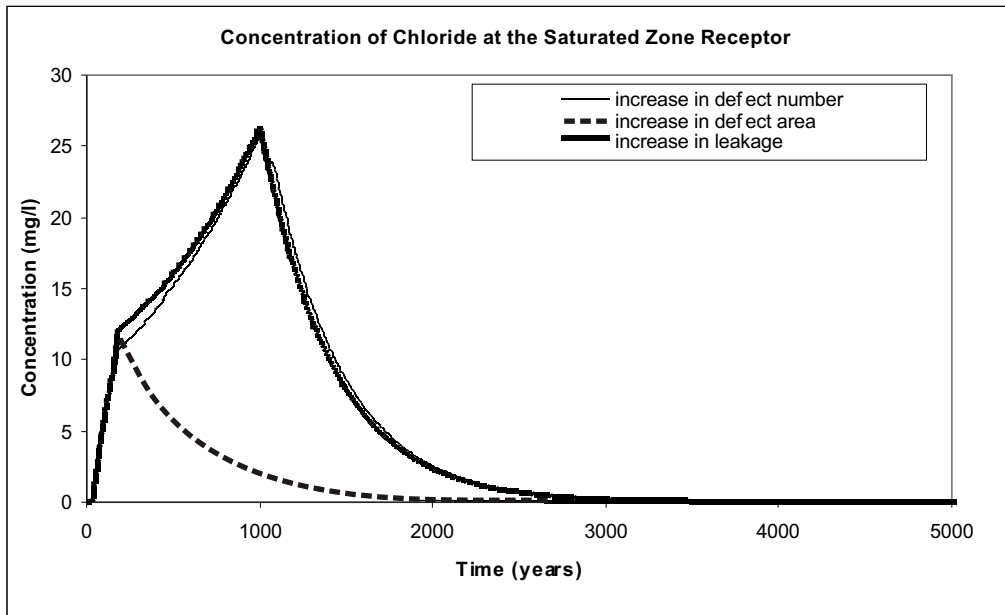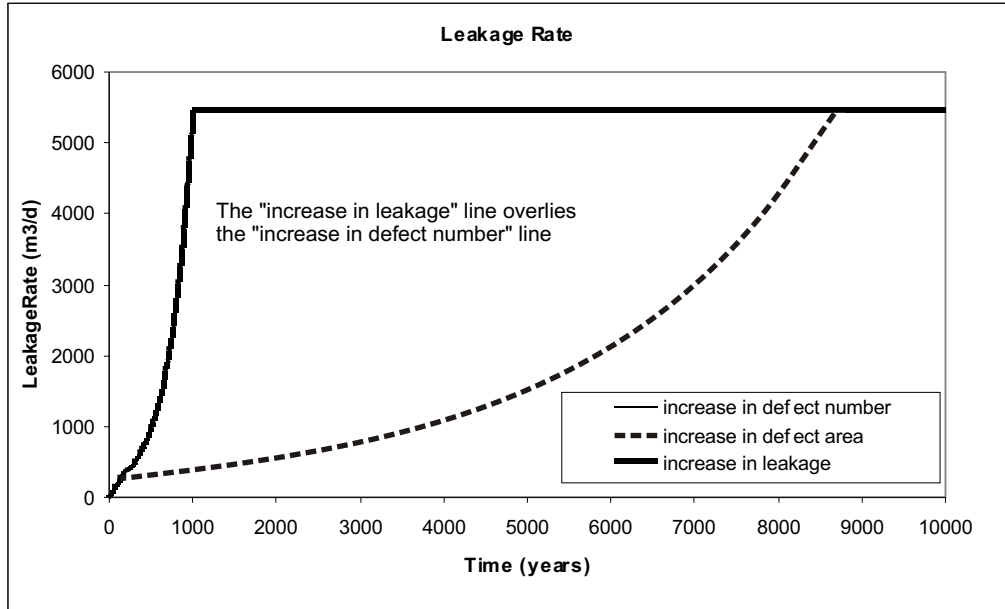
Leakage Rate

The "increase in leakage" line overlies the "increase in defect number" line

— increase in defect number
- - - increase in defect area
— increase in leakage

Concentration of Chloride at the Saturated Zone Receptor

— increase in defect number
- - - increase in defect area
— increase in leakage

Concentration of Cadmium at the Base of the Unsaturated Zone

— increase in defect number
- - - increase in defect area
— increase in leakage

Date	*14/02/03*	*Title*
Project No.	*02523429*	***Sensitivity of predictions to the different concepts of simulating degradation of the FML artificial sealing liners***
Created by	*C.W.*	
File No.	*5219554r2*	

Figure

10

Leakage Rate - Increasing Number Of Defects

- defect number - 100 year half life
- defect number - 200 year half life
- defect number - 300 year half life

Leakage Rate - Increasing Area Of Defects

- defect area - 100 year half life
- defect area - 200 year half life
- defect area - 300 year half life

Leakage Rate- Increasing Leakage Rate

- leakage - 100 year half life
- leakage - 200 year half life
- leakage - 300 year half life
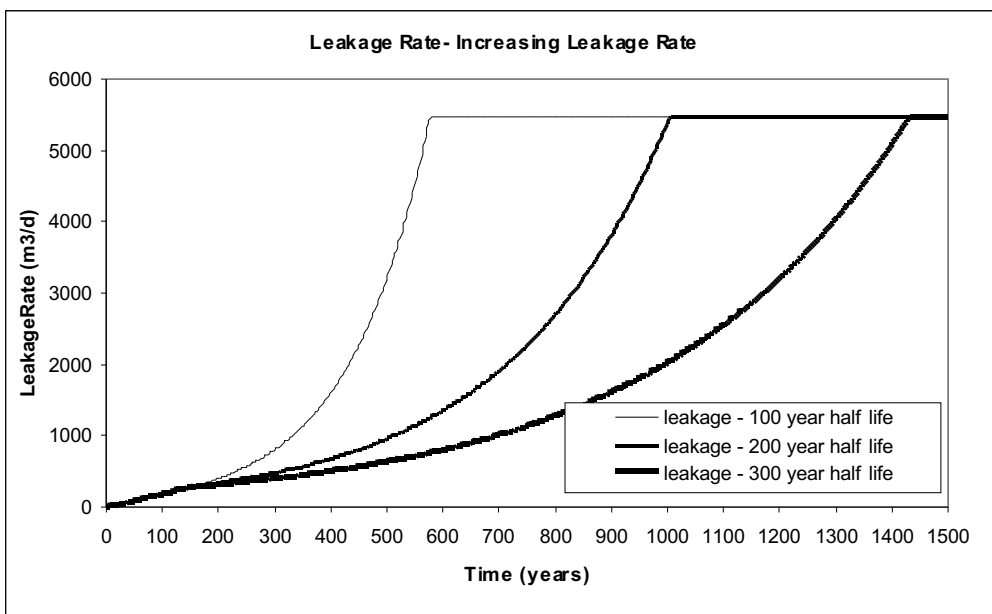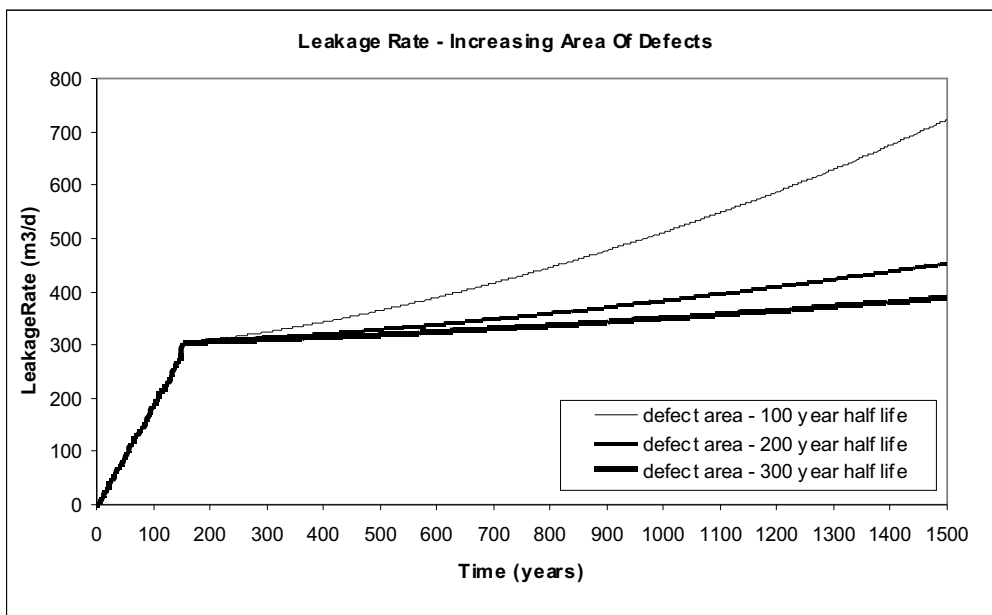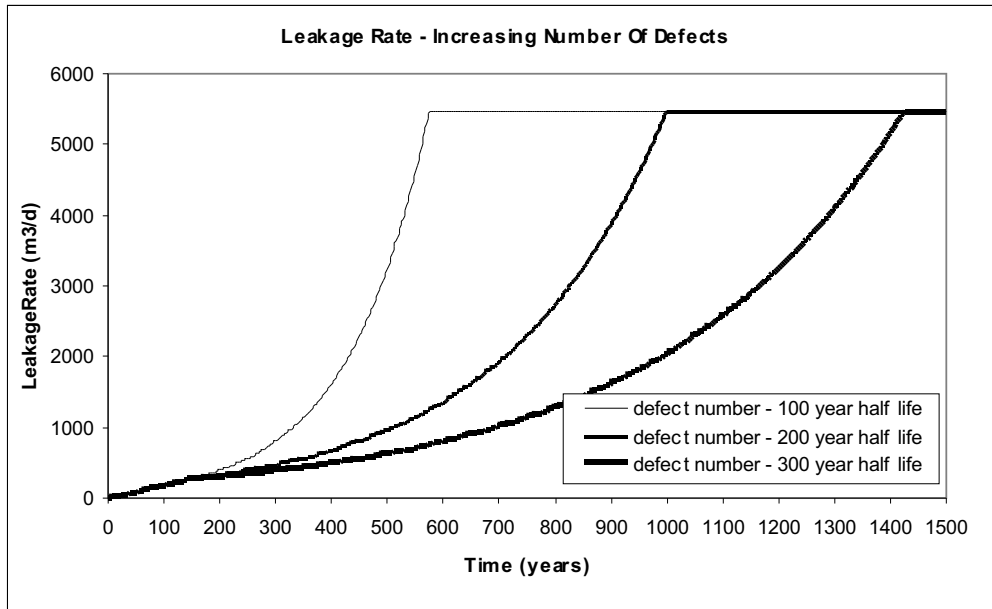
Date	14/02/03	*Title* *Sensitivity of predicted leakage rate to the degradation half life*	*Figure*
Project No.	02523429		**11**
Created by	C.W.		
File No.	5219555r2		
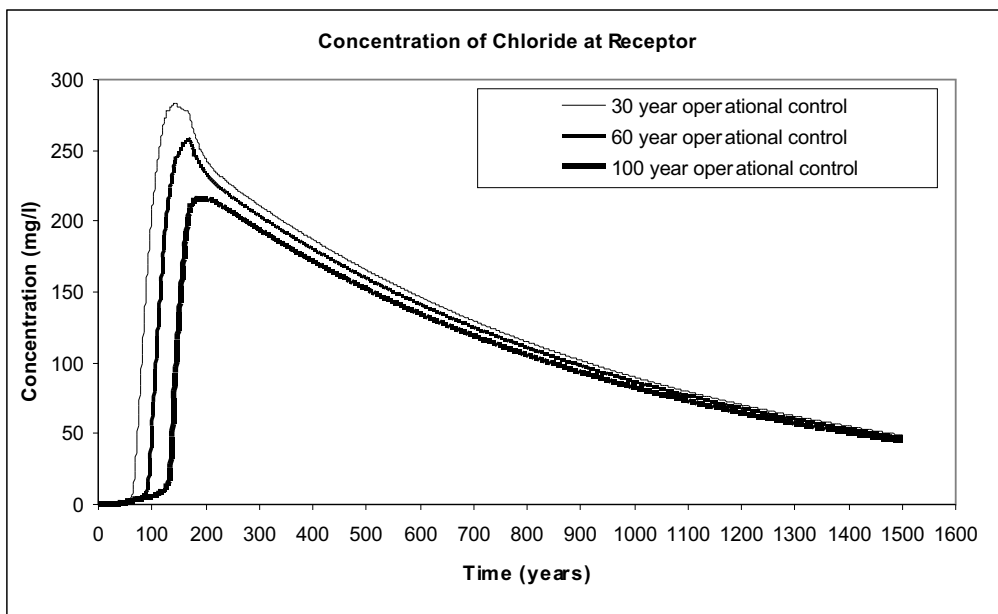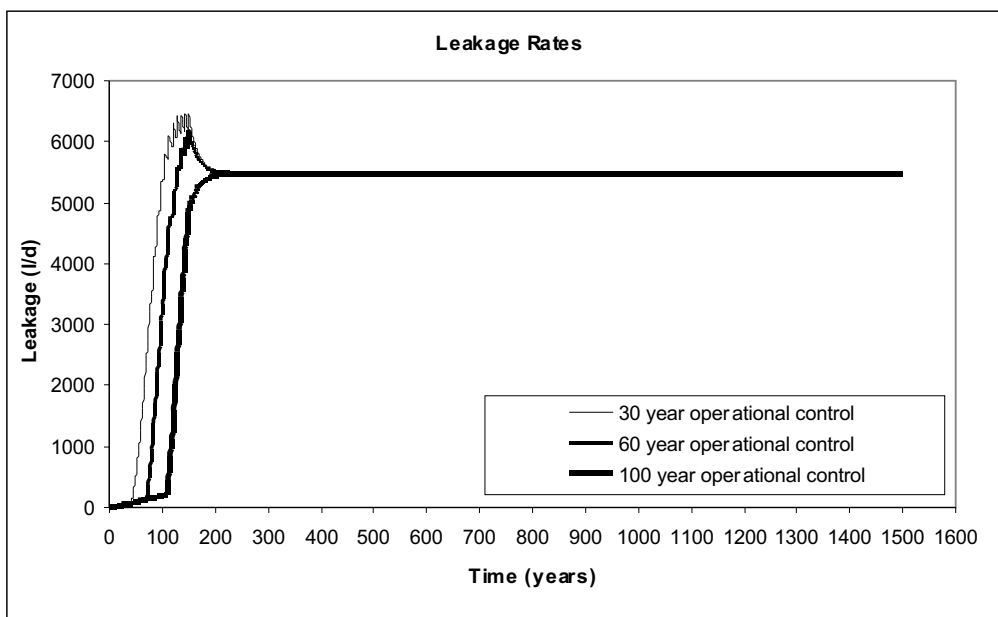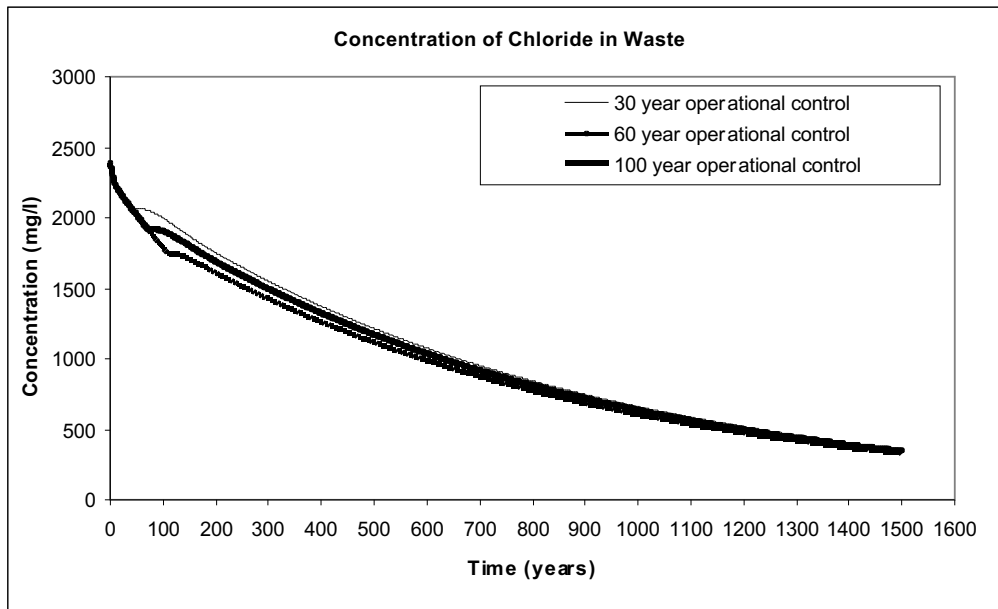
Concentration of Chloride in Waste

Leakage Rates

Concentration of Chloride at Receptor

Cadmium - 40 years management control

Chloride - 40 years management control

Toluene - 40 years management control

Cadmium - 100 years management control

Chloride - 100 years management control

Toluene - 100 years management control

Cadmium - 400 years management control

Chloride - 400 years management control

Toluene - 400 years management control
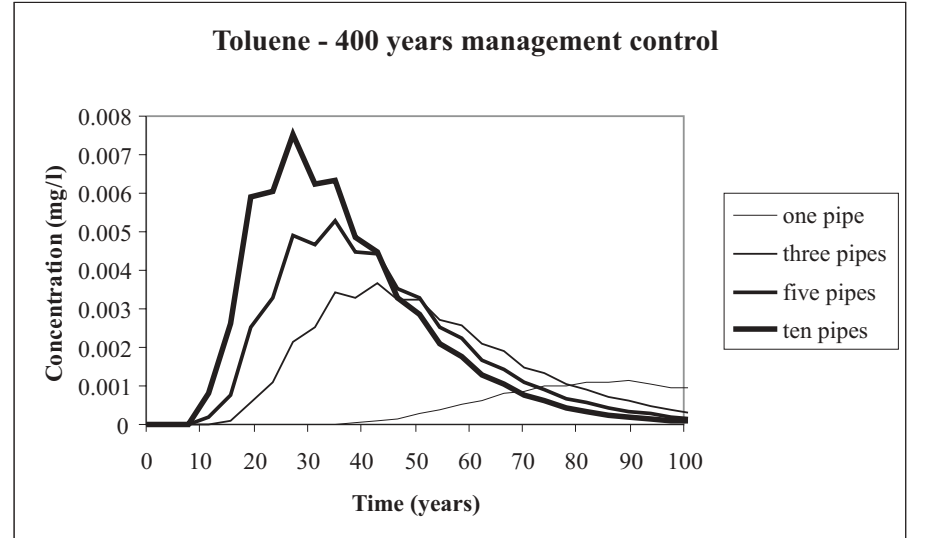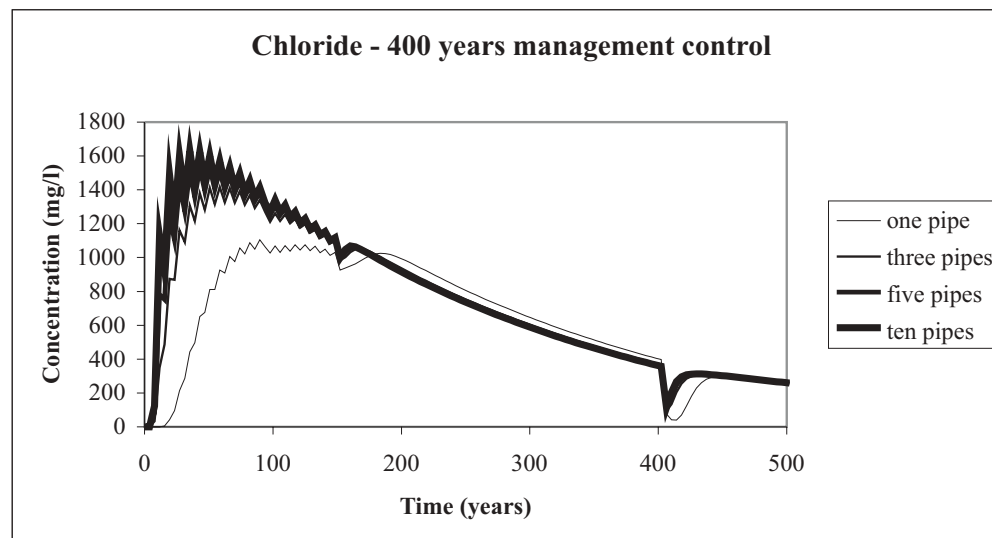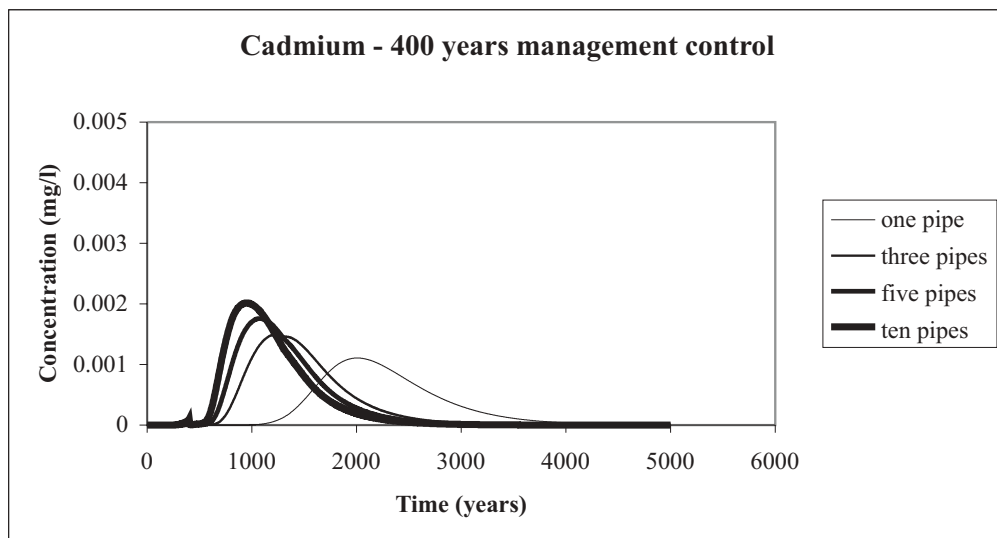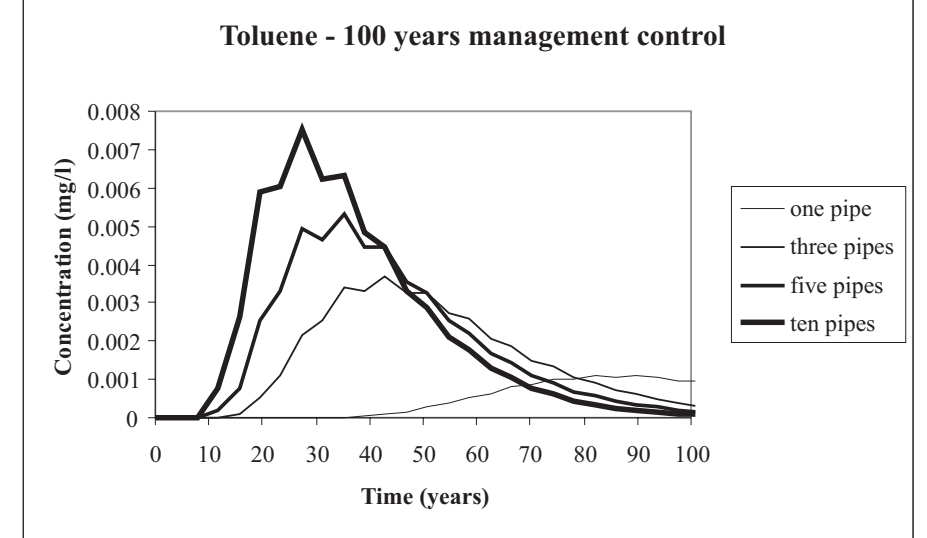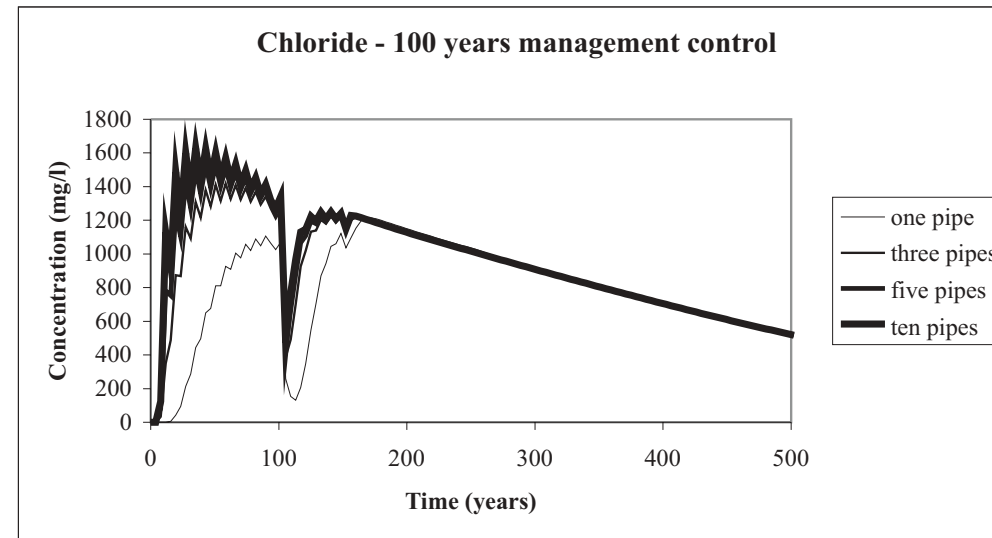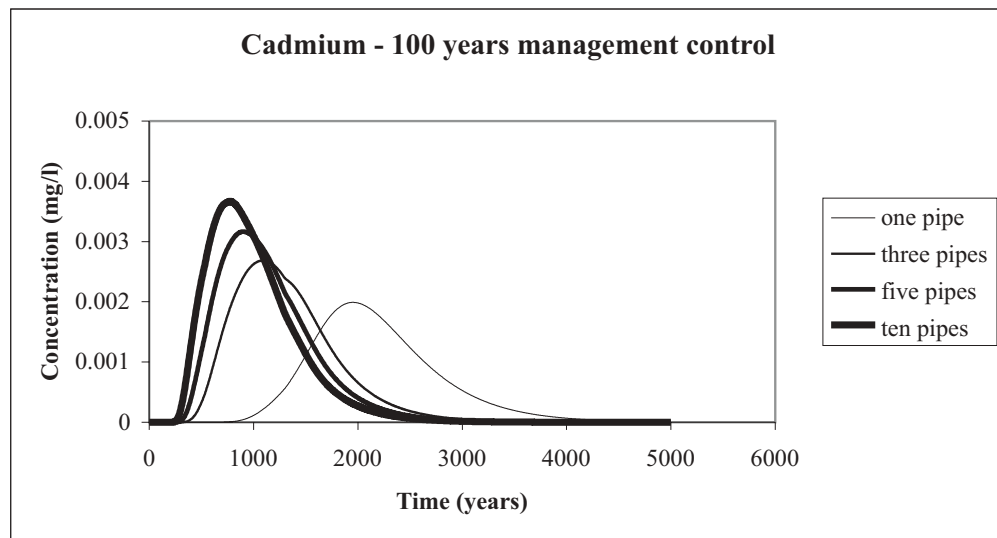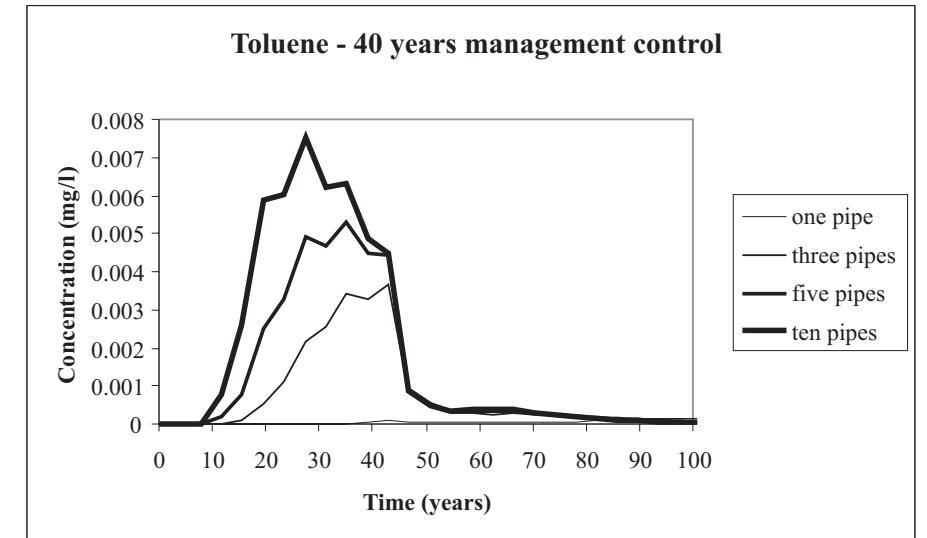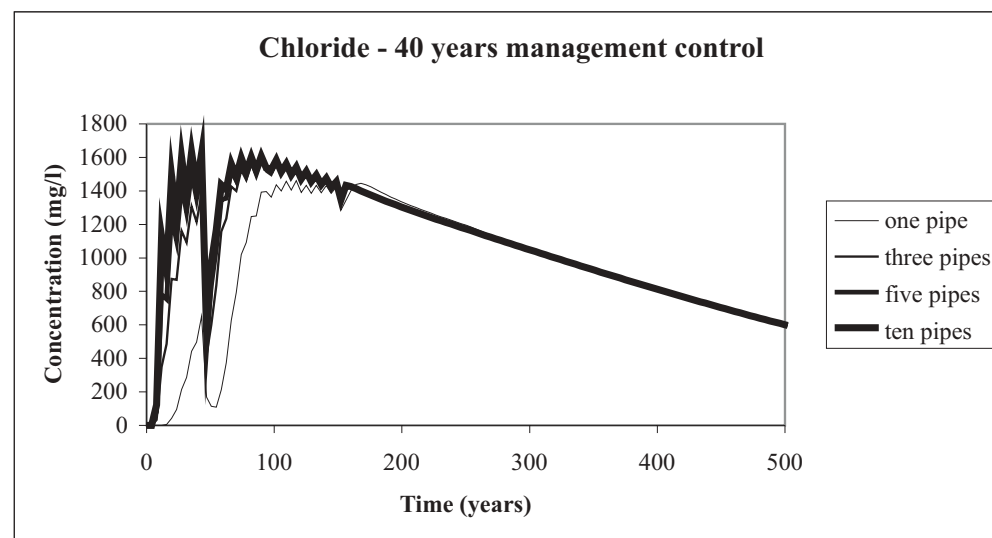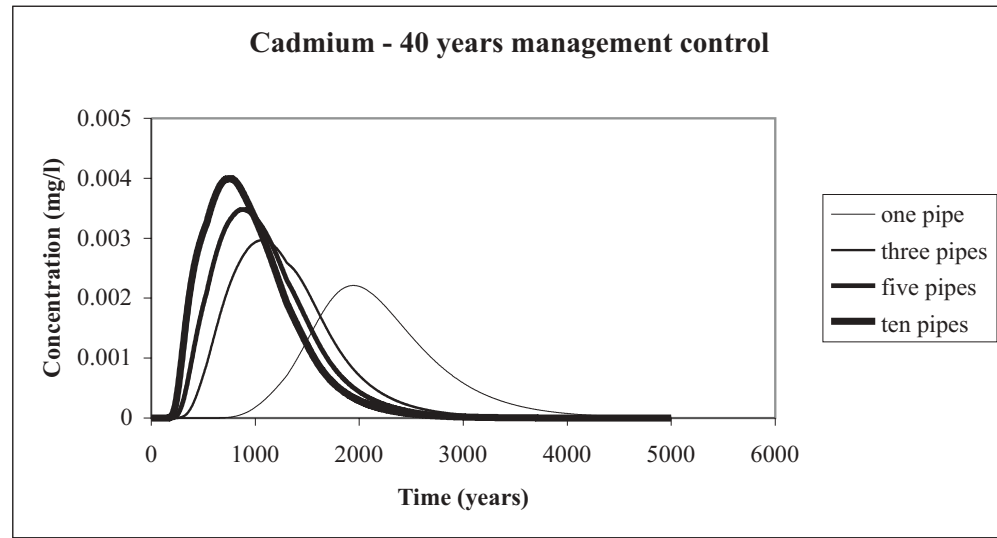
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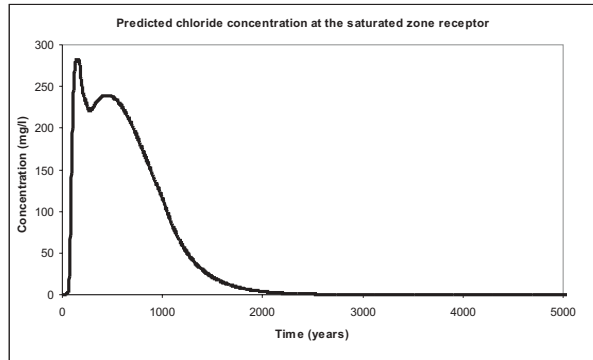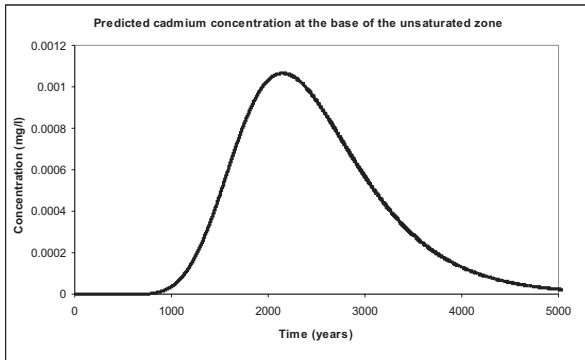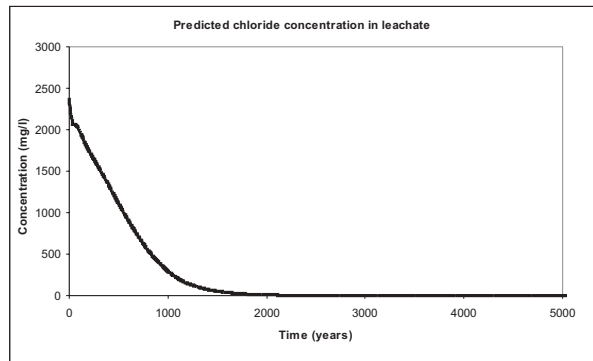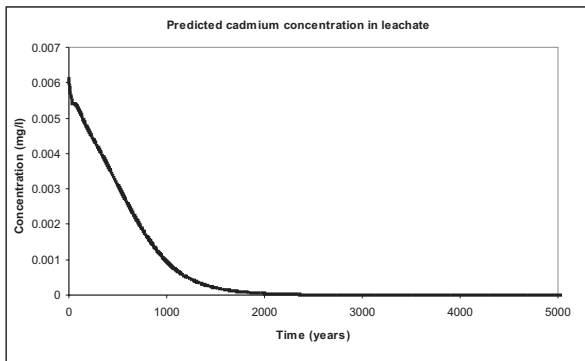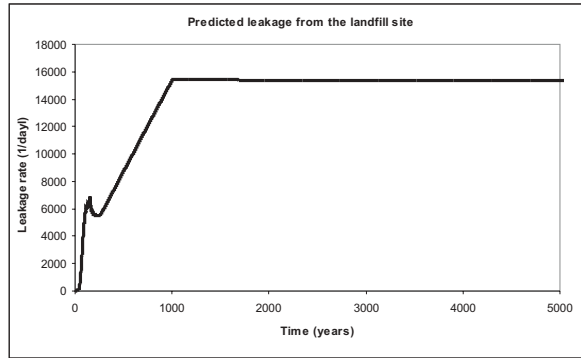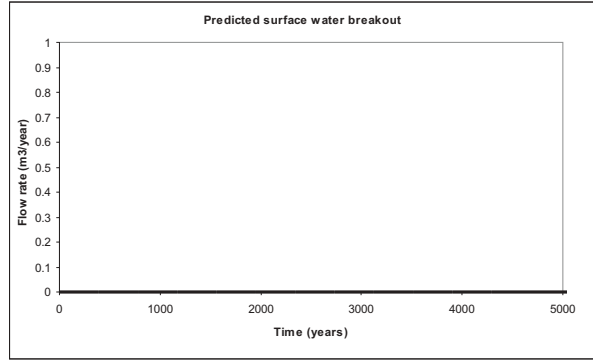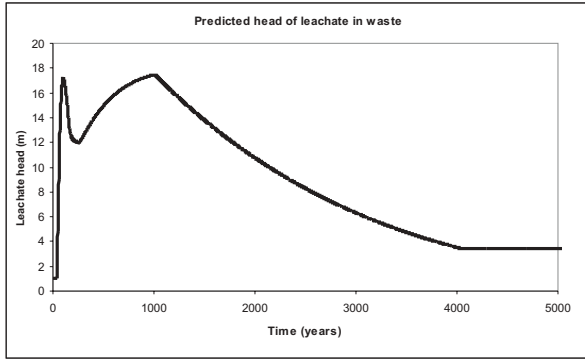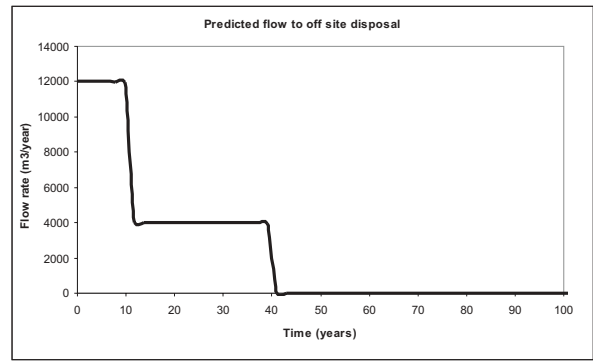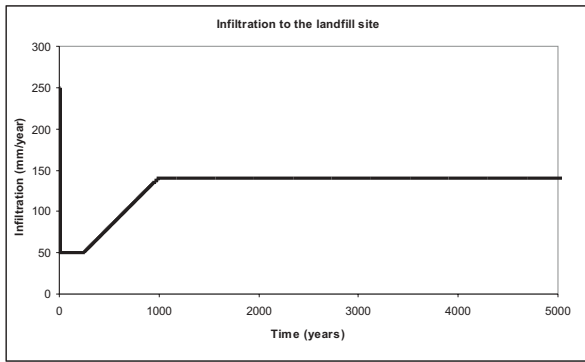
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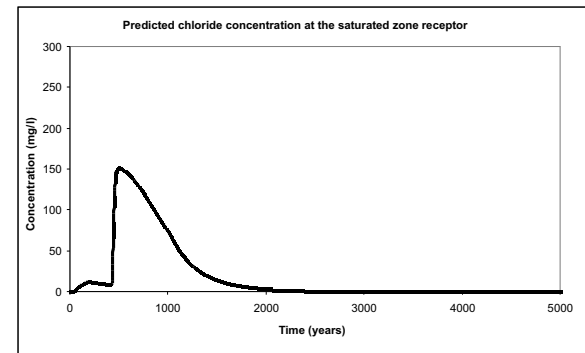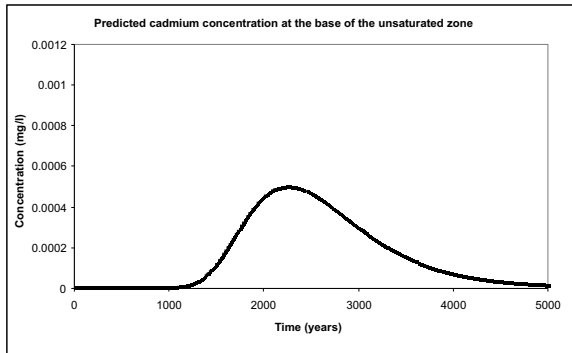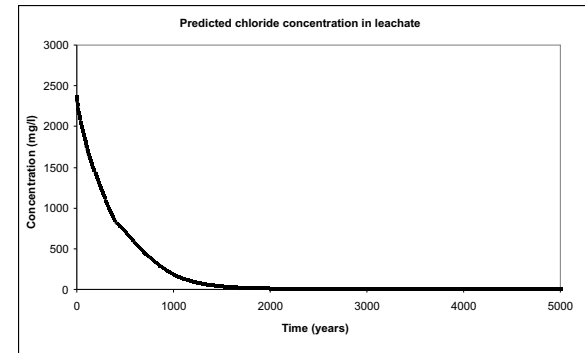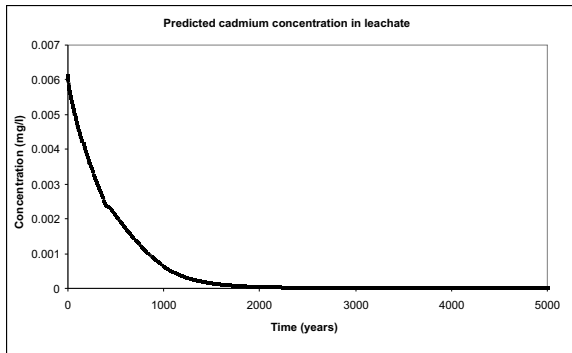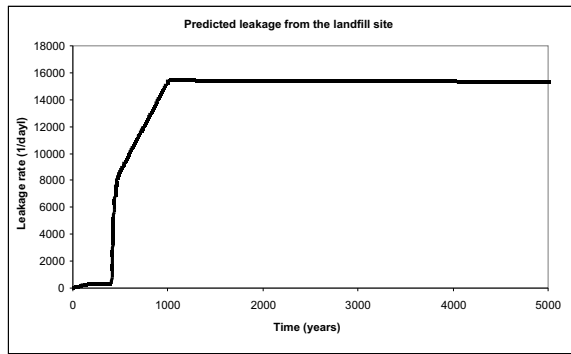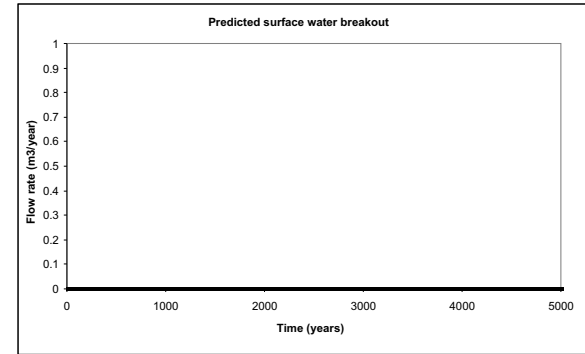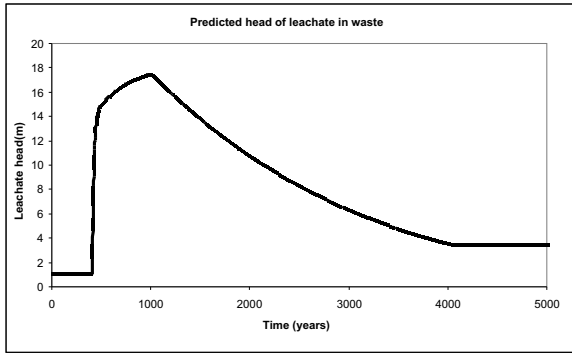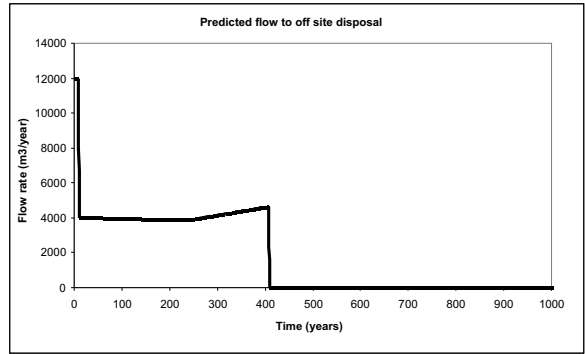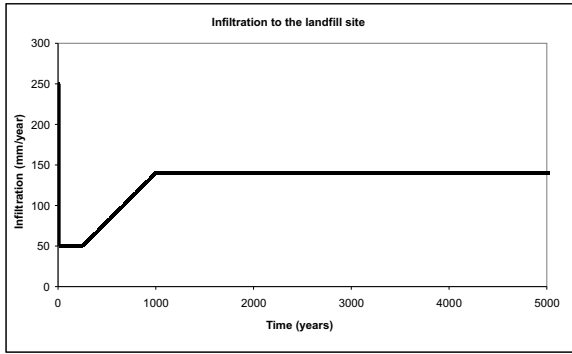
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Date	14/02/03	**Predictions of the base case model - 400 year period of institutional/operational control**	*Figure*
Project No.	02523429		
Created by	C.W.		**15**
File No.	5219686r2		

Appendix 1

Graphical representation of the comparison of spot sampling of leachate data and bulk leachate collection data

Site B Chloride Data

Increasing number of times that spot data are sampled
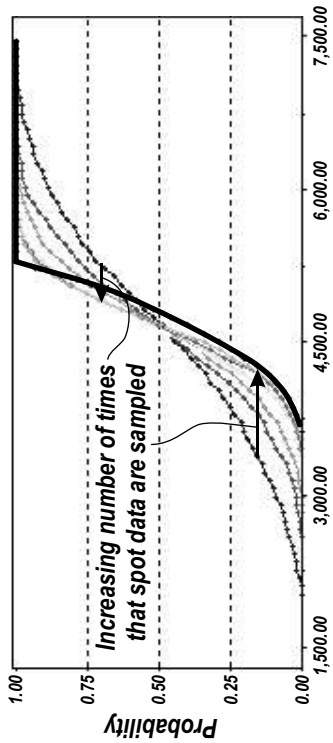
Site D Chloride Data

Increasing number of times that spot data are sampled

Site A Chloride Data

Increasing number of times that spot data are sampled

Site C Chloride Data

Increasing number of times that spot data are sampled

Legend

— *Leachate discharge*

Date	27th November 2002	**Title**
Project No.	02523429	***Graphical representation of the comparison of spot sampling of chloride data and bulk leachate collection data***
Created by	R.W.	
File No.	531667	

Golder Associates

Site B Ammoniacal Nitrogen Data
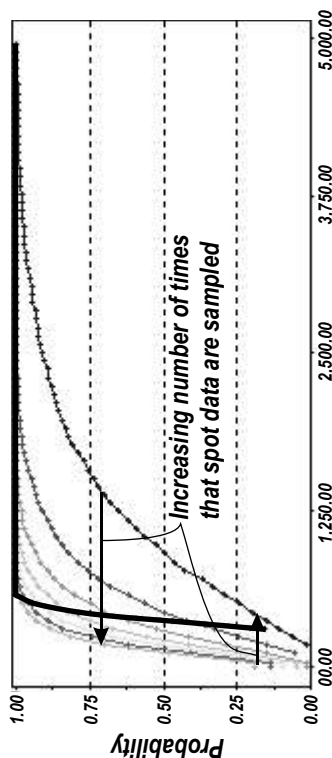
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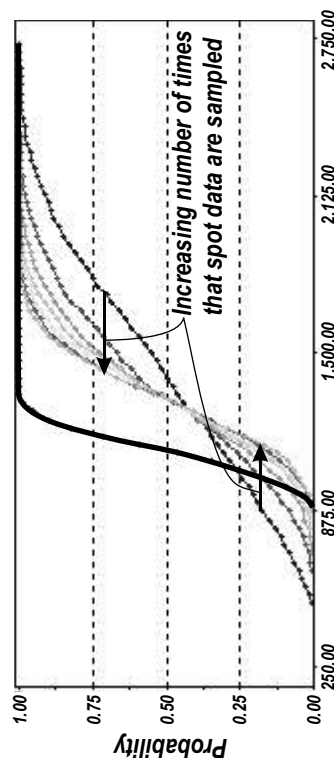
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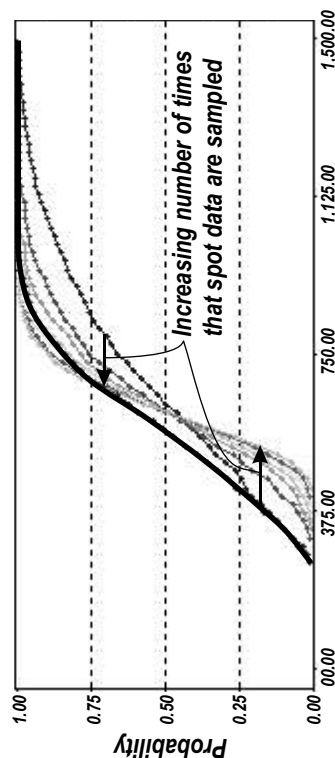
Site A Ammoniacal Nitrogen Data
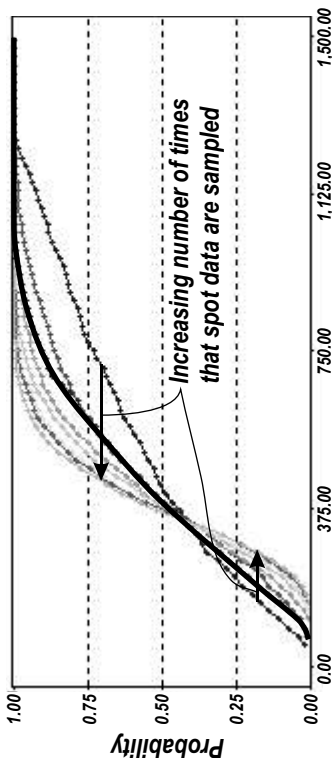
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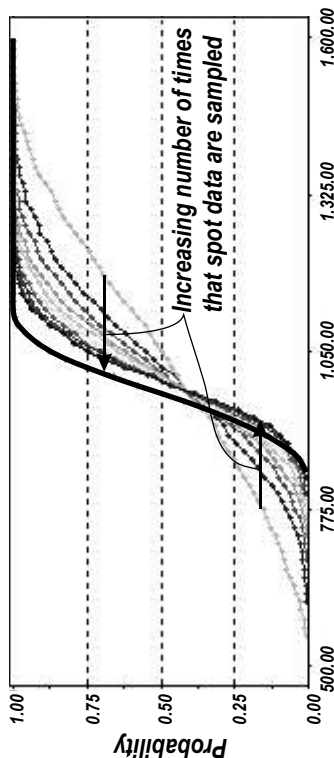
Site E Ammoniacal Nitrogen Data

Increasing number of times that spot data are sampled

Legend

Leachate discharge

Title
Graphical representation of the comparison of spot sampling of ammoniacal nitrogen data and bulk leachate collection data

Appendix 2

Graphical representation of the change in concentration of volatile organic species in leachate

Toluene Site A LM2

$y = 119.73e^{-0.0027x}$
$R^2 = 0.5081$

Toluene Site B LM 3

$y = 1130.4e^{-0.0005x}$
$R^2 = 0.1266$

Toluene Site C (Leachate Drain)

$y = 16.446e^{-0.0002x}$
$R^2 = 0.0816$

Toluene Site A LM1

$y = 74158e^{-0.0043x}$
$R^2 = 0.5226$

Toluene Site B (all monitoring points)

$y = 274.17e^{-0.0004x}$
$R^2 = 0.0523$

Toluene Site B LM6

$y = 649.63e^{-0.0008x}$
$R^2 = 0.2527$
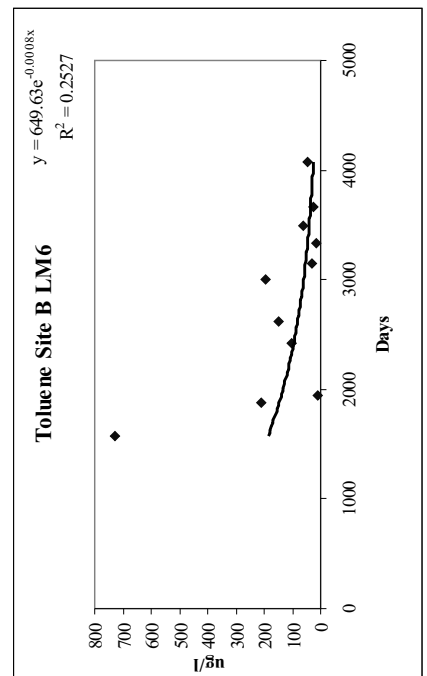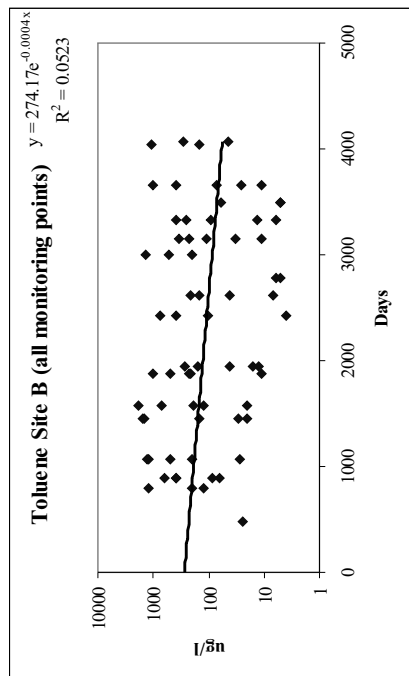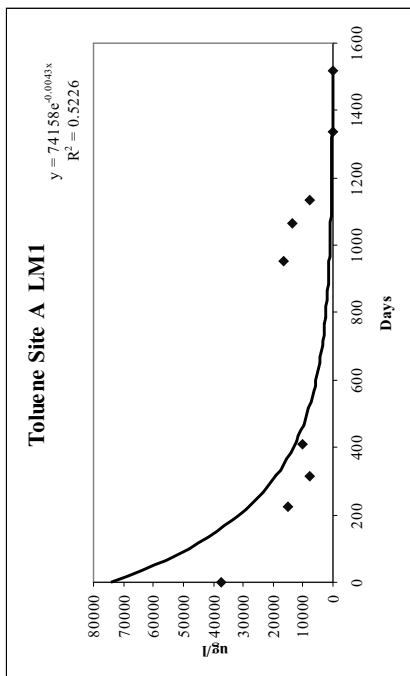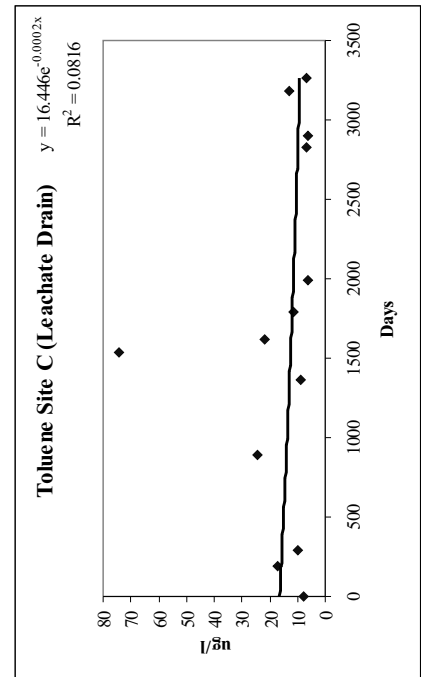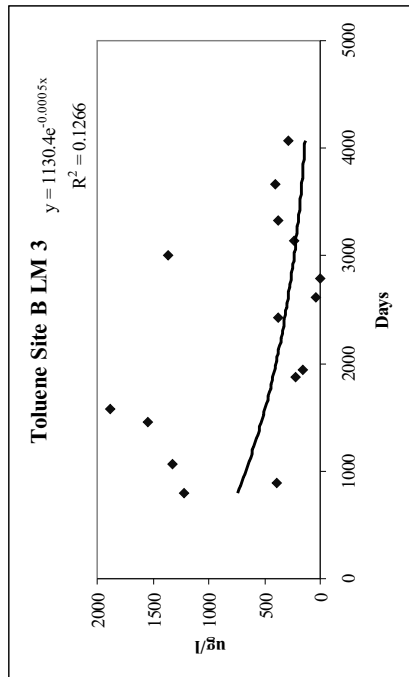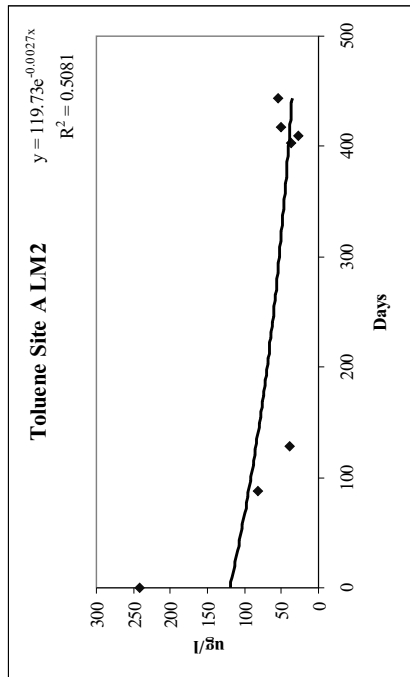
Date	27th November 2002
Project No.	02523429
Created by	R.W.
File No.	531669

Golder Associates

Title
Graphical representation of the change in concentration of toluene in leachate

1,1 Dichloroethane Site A (Total)

$y = 54.52e^{-0.0009x}$
$R^2 = 0.0278$

1,1 Dichloroethane Site A LM 6

$y = 824.77e^{-0.0023x}$
$R^2 = 0.2055$

1,1 Dichloroethane Site B (Total)

$y = 3.929e^{-2E-05x}$
$R^2 = 0.0002$

1,1 Dichloroethane Site B LM3

$y = 20.186e^{-0.0006x}$
$R^2 = 0.2616$

Date 27ᵗʰ *November 2002*	*Title*
Project No. 02523429	***Graphical representation of the change in concentration of***
Created by *R.W.*	***1,1 dichloroethane in leachate***
File No. 531678	

Golder Associates

Benzene Site B LM3

$y = 7044.4e^{-0.001x}$
$R^2 = 0.5619$

Benzene Site C (leachate drain) $y = 85.993e^{-0.0002x}$
$R^2 = 0.0339$

Benzene Site A Total

$y = 9.2696e^{-0.0003x}$
$R^2 = 0.0048$

Benzene Site B Total

$y = 76.06e^{-0.0002x}$
$R^2 = 0.0055$

Date	27th November 2002	Title
Project No.	02523429	*Graphical representation of the change in concentration of benzene in leachate*
Created by	R.W.	
File No.	531670	

Golder Associates

1,2 Dichlorothane Site B LM3

$y = 137.26e^{-0.0007x}$

$R^2 = 0.1885$

ug/l

Days

Golder Associates

Title
Graphical representation of the change in concentration of 1,2 dichlorothane in leachate

Part B

Leach testing of municipal solid waste

CONTENTS

The page numbers refer to those in Part B and are shown at the foot of the page prefixed by 'Part B – '

List of Figures

List of Tables

List of Appendices

1.0 Introduction

1.1 Background to this report

The Environment Agency requested LandSim, a computer model that it uses to assess risk to groundwater quality from landfill sites, to be upgraded so that, amongst other things, account can be taken of developments in the simulation of leachate quality.

The change in concentration of contaminants in leachate in the existing version of LandSim (v2.02) depends on the ratio of the volume of infiltration to the total field capacity of the waste. The rate of change of concentration is the same for all contaminant species. A methodology presented by Hjelmar et al (2001) improves the approach and is contaminant specific. The concentration of a species at any time, C(t) (mg/l), is determined from:

$$C(t) = C_0 \, e^{-(\kappa * LS)}$$

> Where:
>
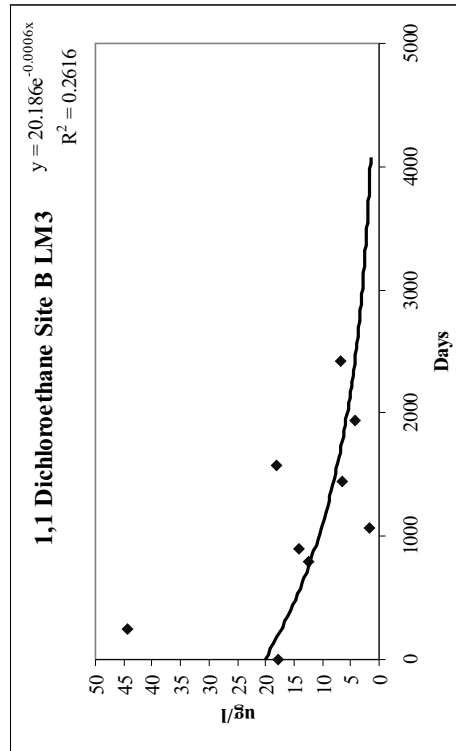> C_0 is the initial concentration of the species in leachate (mg/l), usually determined when LS =
>
> 0.1 l/kg (mg/l)
>
> κ (kappa) is a species and waste specific parameter (kg/l)
>
> LS is the liquid/solid ratio at time t (l/kg).

Whilst the initial concentration can be determined by laboratory testing (C0 when LS=0.1) or by sampling directly from landfills, and the liquid/solid ratio can be readily determined from the waste thickness, density and infiltration, the value of kappa (κ) has to be derived from laboratory column percolation leaching experiments. A contaminant species with a high value of kappa is leached more rapidly from the waste than a species with a low value of kappa; therefore a higher kappa value indicates that the leachate concentration will decrease more rapidly. The kappa value is related to the inverse of the partition coefficient.

H. A. van der Sloot, at the Energy Research Centre of the Netherlands (ECN), has supplied 2,007 experimentally derived values for kappa for several types of solid waste and soils. However, he has no data relating to municipal solid waste (MSW) and has not carried out experiments to determine the leaching behaviour of ammonium.

1.2 Purpose and aims of the report

The purpose of this report is to document the determination of kappa values for the waste acceptance criteria species and ammonium for MSW.

1.3 Report structure

Section 2 follows this introduction and describes the approach that was taken to collect samples of MSW and briefly describes the laboratory testing methodology. Results of the sampling and analysis are presented in Section 3. The data are interpreted in Section 4 to derive values of kappa.

2.0 Sampling and analytical methodology

2.1   Waste sampling methodology

A Golder Associates engineer visited Roxby landfill site in North Lincolnshire on 16th January 2003.

Waste received at Roxby has been pre-treated by the DANO process (a biochemical mechanical process that includes pulverisation). The waste is comprised of three main types: *fines*, *soils product* and *contraries* (larger sized fragments such as plastic bags). According to the site manager, the fines and soil product are visually indistinguishable. Although the waste is pre-treated, it is considered that its leaching behaviour should be representative of municipal solid waste.

On the 15th January 2003 a trench had been excavated through the waste to an approximate depth of 3 m. The waste at the base of the trench was relatively fine grained material with a particle size less than 40 mm. Soils, plastic, paper and glass fragments were evident. According to the site manager, the waste was approximately six months old. The samples were retrieved after removing approximately 0.5 m of covering waste from the sidewall of the trench. The waste was observed to be homogeneous on the scale of about 1 m. The waste samples were observed to be gassing as they were removed. The locations that the waste was removed from were photographed.

Four samples, each of approximately 20 kg of waste, were double bagged in black HDPE sacks and couriered to WRc laboratories in Medmenham for leach testing.

2.2   Analytical methodology

The samples were subject to an upward flow percolation test in accordance with the draft CEN percolation simulation test (European Committee for Standardisation (CEN), 2002).

Cylindrical columns were packed with two to five kilogrammes of waste. The waste was packed to an appropriate density (judgement made by the analyst) and then saturated by allowing water to flow into the bottom of the column. Water was then allowed to flow through the column at a rate of approximately 15 mm/day. Seven samples of leachate were collected over liquid/solid ratios of approximately 0-0.1, 0.1-0.2, 0.2-0.5, 0.5-1.0, 1.0-2.0, 2.0-5.0 and 5.0-10.0. The concentration of antimony, arsenic, cadmium, chromium, copper, dissolved organic carbon, total dissolved solids, phenol, mercury, lead, molybdenum, nickel, zinc, selenium, fluoride, sulphate, chloride and ammonium were determined in each leachate sample.

3.0 Results of sampling and laboratory analysis

3.1 Description of the waste

A sub sample of the waste with a mass of 130 g was analysed in our field laboratory and found to be comprised the following proportions by mass:

9% glass
17% stones
35% paper
35% vegetable matter including organic silt and fines
4% plastics

3.2 Results of laboratory testing

The laboratory results of the analysis are provided in Appendix 1. Plots of the concentration of each contaminant (on a logarithmic scale) against liquid/solid ratio for the five samples are shown in graphical format in Figure 1 and Figure 2. The plots use the mid point of the liquid/solid ratio range over which the samples were collected.

4.0 Interpretation of laboratory results

Kappa values were derived from the results of the laboratory analysis by determining the slope of the linear regression through the liquid/solid ratios, and the corresponding natural logarithm of contaminant concentration. Kappa values were calculated in this manner for each sample and using the entire dataset. Table 1 summarises the results.

The correlation coefficients for the linear regressions were calculated using the Pearson formula. The correlation coefficients and number of data points in the dataset (number of leachate samples with a contaminant concentration above the detection limit) are shown in Table 2. Those results that are not statistically significant at the P=0.01 level are shown in italics in Table 1.

Table 1: Kappa values (kg/l) calculated from laboratory results

Contaminant	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	All samples
Arsenic	*0.23*	*0.21*	0.28	0.28	0.29	0.26
Cadmium	*0.58*	1.65	0.75	0.93	0.85	0.73
Chloride	0.70	0.72	0.70	0.76	0.73	0.72
Chromium	*0.10*	*0.33*	0.20	*0.17*	0.81	0.22
Copper	0.66	1.68	0.64	0.67	0.53	0.60
DOC as C	0.56	0.56	0.56	0.57	0.54	0.56
Fluoride			*0.18*			*0.18*
Molybdenum	0.95	0.84	0.41	0.74	0.65	0.41
Nickel	0.41	0.44	0.48	0.47	0.45	0.45
Lead	0.74	0.73	0.82	1.25	0.86	0.82
Phenol	0.32	0.33	0.41	0.40	0.34	0.36
Antimony	*0.49*	*0.44*	0.49	0.65	0.49	0.51
Sulphate	0.31	0.29	0.31	0.30	0.28	0.30
Zinc	0.59	0.54	0.59	0.59	0.57	0.58
Ammoniacal nitrogen	0.52	0.55	0.63	0.65	0.60	0.59
TDS	0.50	0.50	0.51	0.55	0.51	0.51

The concentrations of mercury and selenium in the leachates were below the laboratory detection limits of 4 µg/l and 9 µg/l, respectively.

Table 2: Correlation coefficient and number of leachate samples above laboratory detection limit

Contaminant	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	All samples
Arsenic	0.88 (7)	0.84 (7)	0.92 (7)	0.89 (7)	0.96 (7)	0.85 (35)
Cadmium	0.84 (6)	0.97 (5)	0.98 (7)	0.99 (6)	1.00 (6)	0.91 (30)
Chloride	0.99 (7)	1.00 (7)	1.00 (7)	1.00 (7)	1.00 (7)	0.99 (35)
Chromium	0.37 (7)	0.79 (7)	0.96 (7)	0.51 (7)	0.99 (6)	0.62 (34)
Copper	0.92 (7)	0.98 (5)	0.97 (7)	0.97 (7)	0.99 (7)	0.85 (33)
DOC as C	1.00 (7)	1.00 (7)	1.00 (7)	1.00 (7)	1.00 (7)	0.99 (35)
Fluoride			0.85 (7)			0.85 (7)
Molybdenum	1.00 (5)	0.99 (5)	0.96 (7)	0.99 (6)	1.00 (6)	0.70 (29)
Nickel	0.99 (7)	0.99 (7)	0.99 (7)	0.98 (7)	0.99 (7)	0.98 (35)
Lead	0.99 (6)	0.98 (6)	0.93 (7)	0.99 (6)	0.99 (7)	0.95 (32)
Phenol	0.96 (7)	0.93 (7)	0.97 (7)	0.97 (7)	0.92 (7)	0.94 (35)
Antimony	0.92 (5)	0.79 (5)	0.99 (5)	0.98 (5)	0.97 (5)	0.83 (25)
Sulphate	0.98 (7)	0.98 (7)	0.98 (7)	0.99 (7)	0.99 (7)	0.99 (35)
Zinc	0.99 (7)	0.97 (7)	0.99 (7)	0.99 (7)	1.00 (7)	0.92 (35)
Ammoniacal nitrogen	1.00 (7)	1.00 (7)	1.00 (7)	1.00 (7)	1.00 (7)	0.99 (35)
TDS	0.99 (7)	0.99 (7)	0.99 (7)	0.99 (7)	1.00 (7)	0.99 (35)

For a number of species a relationship was developed to calculate kappa from initial concentration. The relationships were developed using the results of 2,007 leach tests carried out on several types of solid waste and soils at the Energy Research Centre of the Netherlands (see Part A of this report).

The kappa values derived using all the data in this study of municipal solid waste were compared with the kappa values that would be calculated using the relationship with initial concentration (taken as the average concentration in leachates at a liquid/solid ratio of 0.05) in Table 3.

Table 3: Comparison of MSW kappa values with values calculated from initial concentration

Contaminant	Kappa for MSW from this Study (l/kg)	Average Concentration at LS=0.05 of Five Leaching Tests. Value Taken as Initial Concentration, C_0 (µg/l)	Calculated Value of Kappa (using relationship developed in reference 2) (l/kg)
Arsenic	0.26	208	0.14
Cadmium	0.73	53	0.49
Chloride	0.72	2,880,000	0.74
Chromium	0.22	91	0.28
Copper	0.60	1266	0.43
Fluoride	0.18	2000	0.27
Molybdenum	0.41	249	0.34
Nickel	0.45	1143	0.55
Lead	0.82	1038	0.32
Antimony	0.51	32	0.13
Sulphate	0.30	1,300,000	0.35
Zinc	0.58	12,500	0.44

Table 3 shows a correlation between kappa values derived through laboratory testing and the values that would have been predicted from initial concentrations, using formulae developed from a larger dataset. Notable anomalies are lead and antimony, which appear to be more readily flushed from MSW than would have been predicted.

5.0 Conclusions of the study

Leaching tests were carried out on samples of municipal solid waste to derive the value of kappa for waste acceptance criteria species and ammonium. Ammonium was found to be flushed from waste less readily than chloride. The kappa values are broadly consistent with a larger dataset supplied by the Energy Research Centre of the Netherlands. Notable anomalies are lead and antimony, which appear to be more readily flushed from MSW than would have been predicted.

5.1   Acknowledgements

6.0 References

CEN, 2002. *Leaching behaviour test - upflow percolation test*. Draft prEN 14405. CEN/TC292/WG6. April 2002

Hjelmar, O., van der Sloot, H. A., Guyonnet, D., Rietra, R .P. J. J., Brun, A., and Hall, D., 2001. *Development of acceptance criteria for landfilling of waste: an approach based on impact modelling and scenario calculations*. Proceedings Sardinia 2001, Eighth International Waste Management and Landfill Symposium.

Figures
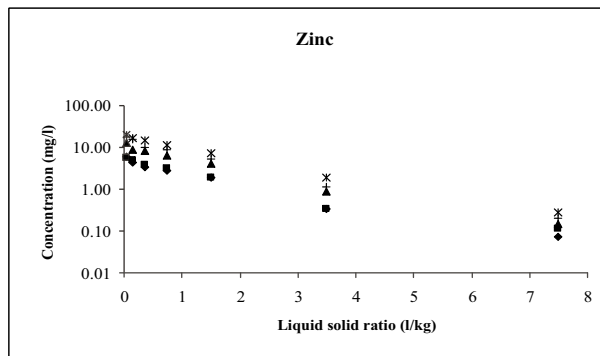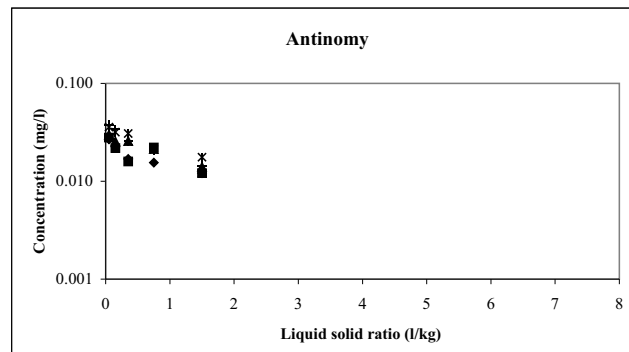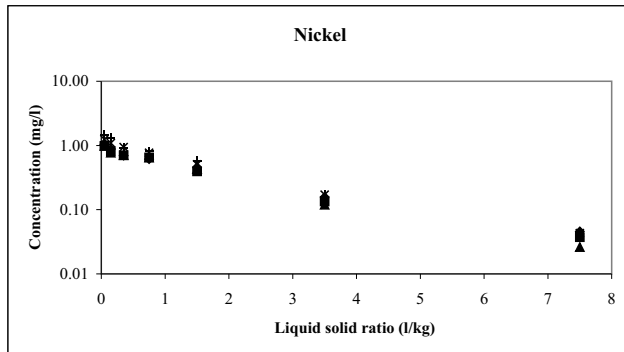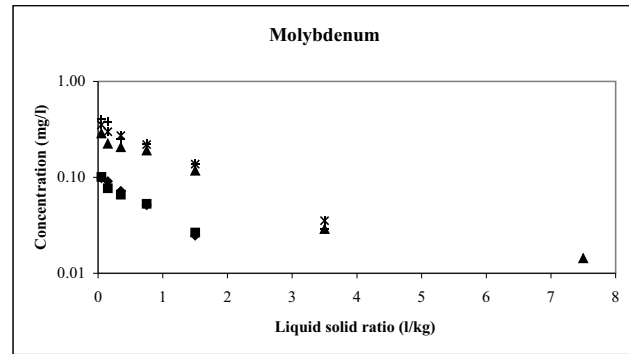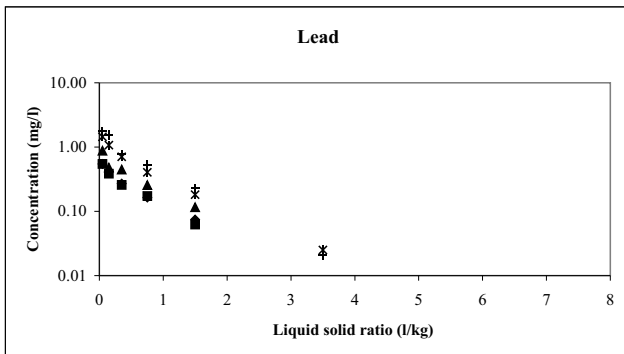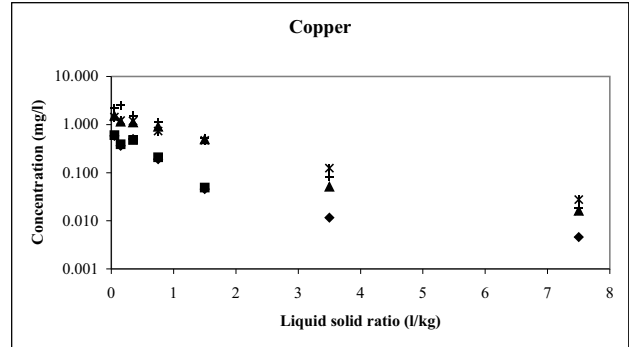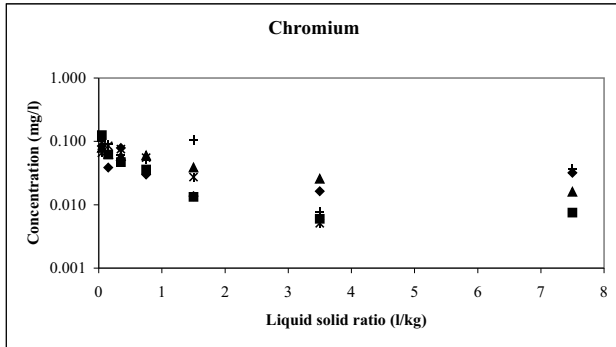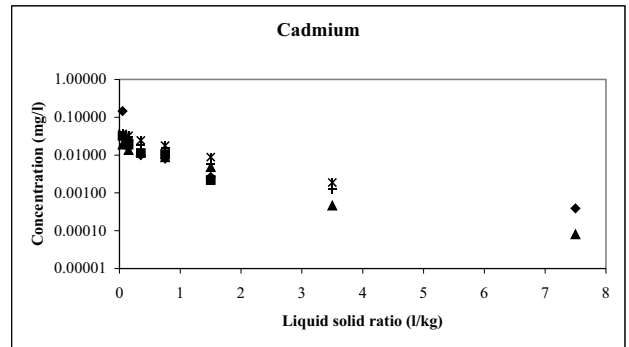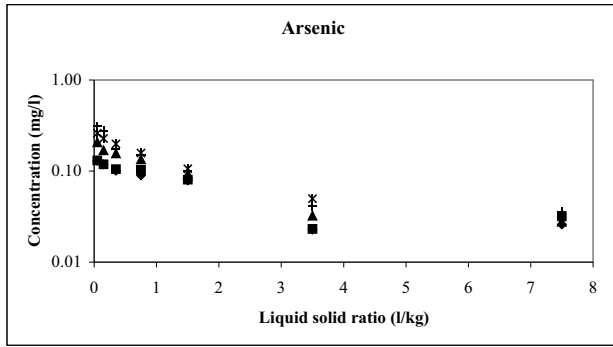
Results of leaching tests for metallic contaminants

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Project No.	02523429
Created by	C.W.
File No.	5220079

Title: **Results of leaching tests for metallic contaminants**

Figure 1
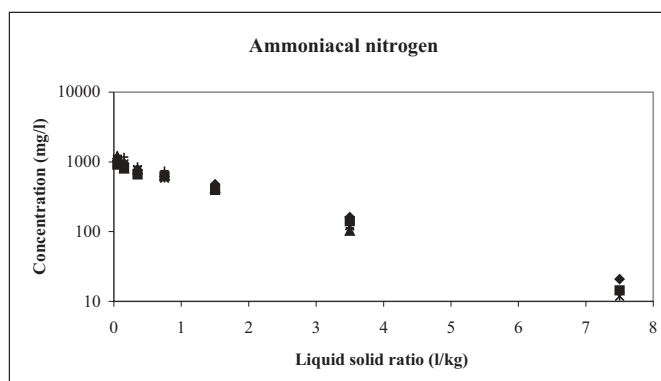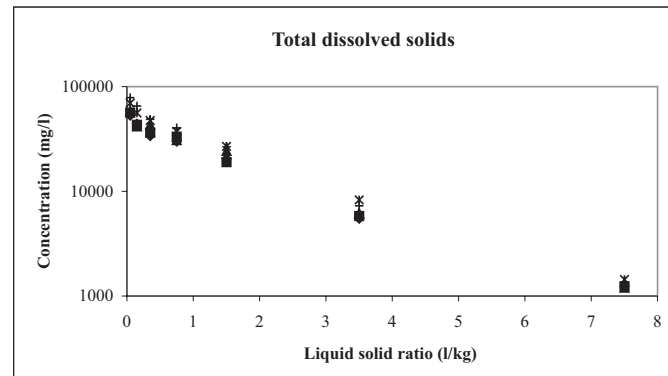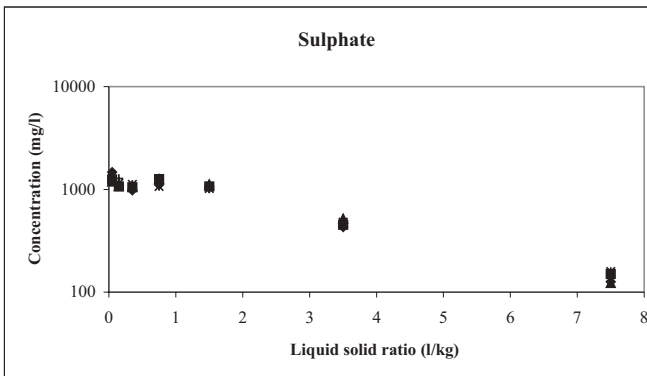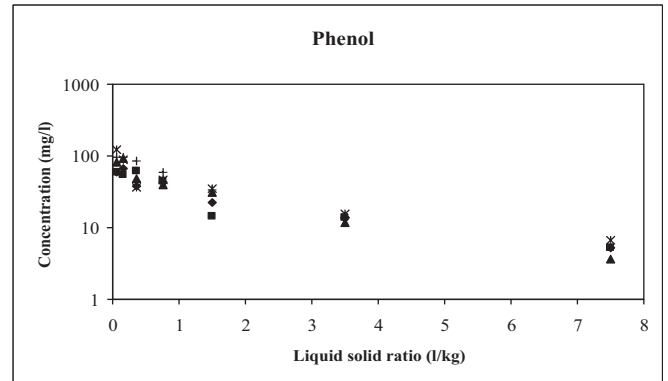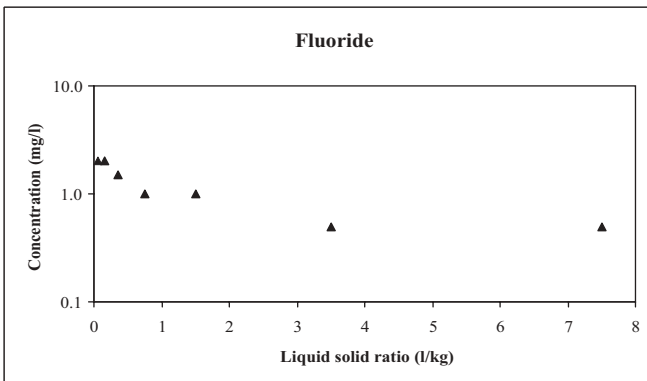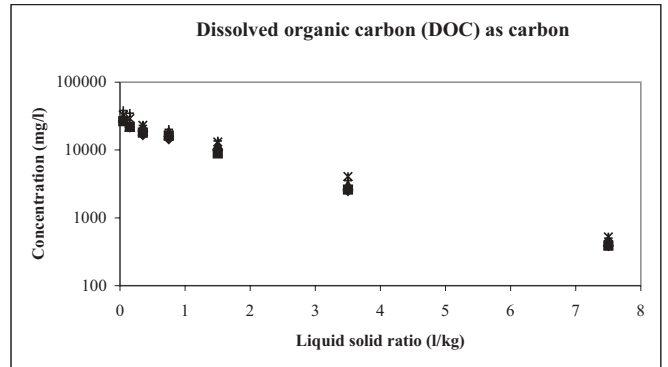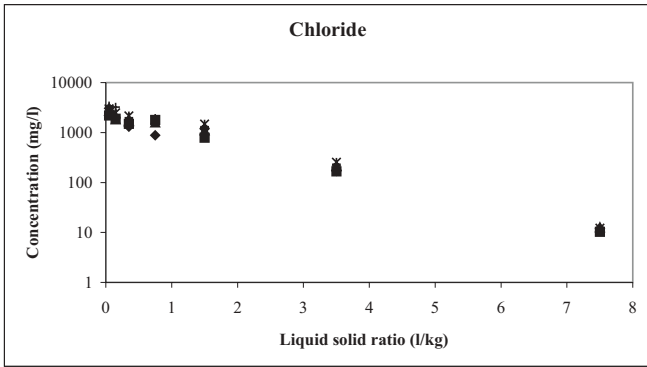
Results of leaching tests for non metallic contaminants

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Figure

2

Appendix 1

Results of laboratory analysis

WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	Number of Samples Received	5	
Company	Golder Associates	Date Samples Received	17/02/03	
Client Reference	DANO MSW	Sample Types	prEN 14405 Leach Test Extract	
WRc-NSF Reference	N18955/N	WRc-NSF Contract Number	13113-0	

Sample Code	As mg/l	Cd mg/l	Cl mg/l	Cr mg/l	Cu mg/l	DOC mg/l C	F mg/l	Hg mg/l	Mo mg/l	Ni mg/l	Pb mg/l	Phenol mg/l	Sb mg/l	Se mg/l	SO4 mg/l	Zn mg/l	NH3 mg/l N	TDS mg/l	pH -
REP 1																			
L/S = 0.0 - 0.1 l/kg	0.130	0.146	3050	0.085	0.584	27200	<2.0	<0.004	0.098	1.04	0.547	58.0	0.027	<0.009	1470	6.02	1130	52800	5.93
L/S = 0.1 - 0.2 l/kg	0.119	0.025	1970	0.039	0.361	21600	<2.0	<0.004	0.091	0.881	0.417	68.0	0.023	<0.009	1100	4.47	957	44200	5.93
L/S = 0.2 - 0.5 l/kg	0.101	0.010	1310	0.079	0.501	16600	<1.5	<0.004	0.072	0.694	0.271	38.0	0.017	<0.009	981	3.37	765	33800	5.84
L/S = 0.5 - 1.0 l/kg	0.090	0.0080	885	0.030	0.191	14500	<1.0	<0.004	0.051	0.614	0.164	42.5	0.016	<0.009	1110	2.85	618	29900	5.83
L/S = 1.0 - 2.0 l/kg	0.079	0.0027	1190	0.014	0.046	9730	<1.0	<0.004	0.025	0.461	0.0748	22.2	0.012	<0.009	1070	1.89	478	20500	6.08
L/S = 2.0 - 5.0 l/kg	0.023	<0.00007	170	0.016	0.012	2490	<0.5	<0.004	<0.012	0.158	<0.001	13.7	<0.01	<0.009	431	0.341	162	5480	6.16
L/S = 5.0 - 10.0 l/kg	0.026	0.0004	12.1	0.032	0.005	387	<0.5	<0.004	<0.012	0.046	0.0017	5.20	<0.01	<0.009	126	0.072	20.8	1240	6.37
Prepn Ref	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14407	prEN14405
Method Ref	ING113	ING113	ING25$	ING113	ING113	ING52	$	ING75	ING113	ING113	ING113	$	ING95	ING113	ING25$	ING28	ING24	ING90	ING85
Run date	06/04/03	06/04/03	01/04/03	06/04/03	06/04/03	12/03/03	13/04/03	21/03/03	06/04/03	06/04/03	06/04/03	11/04/03	04/04/03	06/04/03	01/04/03	16/04/03	19/03/03	16/04/03	06/03/03

Reported by :

John Dunning
Test Area Manager

Date of Report: 16/04/03   Report Page 1 of 2

WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury
Company	Golder Associates
Client Reference	DANO MSW
WRc-NSF Reference	N18955/N

Number of Samples Received	5
Date Samples Received	17/02/03
Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Contract Number	13113-0

Sample Code	As mg/kg		Cd mg/kg		Cl mg/kg		Cr mg/kg		Cu mg/kg		DOC mg/kg		F mg/kg		Hg mg/kg		TDS mg/kg	
REP 1	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.013	0.013	0.0146	0.015	305	305	0.0085	0.0085	0.058	0.058	2720	2720	<0.2	<0.2	<0.0004	0.0004	5280	5280
L/S = 0.1 - 0.2 l/kg	0.012	0.025	0.0025	0.017	197	502	0.0039	0.0123	0.036	0.095	2160	4880	<0.2	<0.4	<0.0004	0.0008	4420	9700
L/S = 0.2 - 0.5 l/kg	0.030	0.055	0.0030	0.020	393	895	0.0237	0.0360	0.150	0.245	4980	9860	<0.45	<0.85	<0.0012	0.002	10140	19840
L/S = 0.5 - 1.0 l/kg	0.045	0.100	0.0040	0.024	443	1338	0.015	0.0510	0.096	0.340	7250	17110	<0.5	<1.35	<0.002	0.004	14950	34790
L/S = 1.0 - 2.0 l/kg	0.079	0.179	0.0027	0.027	1190	2528	0.014	0.0647	0.046	0.386	9730	26840	<1.0	<2.35	<0.004	0.008	20500	55290
L/S = 2.0 - 5.0 l/kg	0.068	0.247	<0.00021	<0.027	510	3038	0.049	0.114	0.035	0.421	7470	34310	<1.5	<3.85	<0.012	0.020	16440	71730
L/S = 5.0 - 10.0 l/kg	0.130	0.377	0.0020	<0.029	60.5	3098	0.160	0.273	0.023	0.444	1935	36245	<2.5	<6.35	<0.02	0.040	6200	77930

Sample Code	Mo mg/kg		Ni mg/kg		Pb mg/kg		Phenol mg/kg		Sb mg/kg		Se mg/kg		SO4 mg/kg		Zn mg/kg		NH3 mg/kg (as N)	
REP 1	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.010	0.010	0.104	0.104	0.0547	0.055	5.80	5.80	0.0027	0.003	<0.0009	<0.0009	147	147	0.602	0.602	113	113
L/S = 0.1 - 0.2 l/kg	0.009	0.019	0.088	0.192	0.0417	0.096	6.80	12.6	0.0023	0.005	<0.0009	<0.0018	110	257	0.447	1.05	95.7	209
L/S = 0.2 - 0.5 l/kg	0.022	0.041	0.208	0.400	0.0813	0.178	11.4	24.0	0.0051	0.010	<0.0027	<0.0045	294	551	1.01	2.06	230	438
L/S = 0.5 - 1.0 l/kg	0.026	0.066	0.307	0.707	0.0820	0.260	21.3	45.3	0.0078	0.018	<0.0045	<0.009	555	1106	1.43	3.49	309	747
L/S = 1.0 - 2.0 l/kg	0.025	0.091	0.461	1.17	0.0748	0.335	22.2	67.5	0.0121	0.030	<0.009	<0.018	1070	2176	1.89	5.38	478	1225
L/S = 2.0 - 5.0 l/kg	<0.036	<0.127	0.474	1.64	<0.003	<0.338	41.1	109	<0.03	<0.06	<0.027	<0.045	1293	3469	1.02	6.40	486	1711
L/S = 5.0 - 10.0 l/kg	<0.06	<0.187	0.230	1.87	0.0083	<0.346	26.0	135	<0.05	<0.11	<0.045	<0.09	630	4099	0.360	6.76	104	1815

Reported by :

John Dunning
Test Area Manager

Date of Report: 16/04/03

WRc-NSF Ltd, Henley Road, Medmenham, Marlow, Bucks SL7 2HD, UK. Tel: +44 (0) 1491 636500. Fax: +44 (0) 1491 636501. Email: analysis@wrcplc.co.uk

WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	Number of Samples Received	5
Company	Golder Associates	Date Samples Received	17/02/03
Client Reference	DANO MSW	Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Reference	N18955/N19124	WRc-NSF Contract Number	13113-0

Sample Code	As mg/l	Cd mg/l	Cl mg/l	Cr mg/l	Cu mg/l	DOC mg/l C	F mg/l	Hg mg/l	Mo mg/l	Ni mg/l	Pb mg/l	Phenol mg/l	Sb mg/l	Se mg/l	SO4 mg/l	Zn mg/l	NH3 mg/l N	TDS mg/l	pH -
REP 2																			
L/S = 0.0 - 0.1 l/kg	0.131	0.032	2200	0.126	0.606	26600	<2.0	<0.004	0.101	0.982	0.547	60.0	0.028	<0.009	1250	5.78	913	56400	6.06
L/S = 0.1 - 0.2 l/kg	0.119	0.019	1900	0.062	0.392	22000	<2.0	<0.004	0.077	0.817	0.386	54.0	0.022	<0.009	1070	4.81	810	43200	6.02
L/S = 0.2 - 0.5 l/kg	0.105	0.011	1500	0.047	0.479	18000	<1.5	<0.004	0.066	0.704	0.257	62.0	0.016	<0.009	1050	3.72	662	36300	5.98
L/S = 0.5 - 1.0 l/kg	0.103	0.011	1780	0.036	0.210	16300	<1.0	<0.004	0.053	0.654	0.173	45.0	0.022	<0.009	1260	3.23	624	33300	5.85
L/S = 1.0 - 2.0 l/kg	0.081	0.002	785	0.013	0.049	8930	<1.0	<0.004	0.027	0.394	0.062	14.4	0.012	<0.009	1070	1.92	397	19000	6.04
L/S = 2.0 - 5.0 l/kg	0.023	<0.00007	167	0.006	<0.003	2610	<0.5	<0.004	<0.012	0.134	<0.001	13.8	<0.01	<0.009	452	0.343	141	5800	5.96
L/S = 5.0 - 10.0 l/kg	0.032	<0.00007	10.3	0.008	<0.003	389	<0.5	<0.004	<0.012	0.037	0.002	5.15	<0.01	<0.009	150	0.114	14.4	1240	6.28

	As	Cd	Cl	Cr	Cu	DOC	F	Hg	Mo	Ni	Pb	Phenol	Sb	Se	SO4	Zn	NH3	TDS	pH
Prepn Ref	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14407	prEN14405
Method Ref	ING113	ING113	ING25$	ING113	ING113	ING52	$	ING75	ING113	ING113	ING113	$	ING95	ING113	ING25$	ING28	ING24	ING90	ING85
Run date	06/04/03	06/04/03	01/04/03	06/04/03	06/04/03	12/03/03	13/04/03	21/03/03	06/04/03	06/04/03	06/04/03	11/04/03	04/04/03	06/04/03	01/04/03	16/04/03	19/03/03	16/04/03	06/03/03

Reported by :

John Dunning
Test Area Manager

Date of Report: 16/04/03   Report Page 1 of 2

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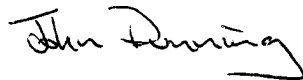
WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	
Company	Golder Associates	
Client Reference	DANO MSW	
WRc-NSF Reference	N18955/N19124	

Number of Samples Received	5	
Date Samples Received	17/02/03	
Sample Types	prEN 14405 Leach Test Extract	
WRc-NSF Contract Number	13113-0	

Sample Code	As mg/kg		Cd mg/kg		Cl mg/kg		Cr mg/kg		Cu mg/kg		DOC mg/kg		F mg/kg		Hg mg/kg		TDS mg/kg	
REP 2	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.013	0.013	0.0032	0.003	220	220	0.013	0.013	0.061	0.061	2660	2660	<0.2	<0.2	<0.0004	<0.0004	5640	5640
L/S = 0.1 - 0.2 l/kg	0.012	0.025	0.0019	0.005	190	410	0.006	0.019	0.039	0.100	2200	4860	<0.2	<0.4	<0.0004	<0.0008	4320	9960
L/S = 0.2 - 0.5 l/kg	0.032	0.057	0.0034	0.008	450	860	0.014	0.033	0.144	0.244	5400	10260	<0.45	<0.85	<0.0012	<0.002	10890	20850
L/S = 0.5 - 1.0 l/kg	0.052	0.108	0.0053	0.014	890	1750	0.018	0.051	0.105	0.349	8150	18410	<0.5	<1.35	<0.002	<0.004	16650	37500
L/S = 1.0 - 2.0 l/kg	0.081	0.189	0.0022	0.016	785	2535	0.013	0.064	0.049	0.398	8930	27340	<1.0	<2.35	<0.004	<0.008	19000	56500
L/S = 2.0 - 5.0 l/kg	0.070	0.258	<0.00021	<0.016	501	3036	0.018	0.082	<0.009	<0.407	7830	35170	<1.5	<3.85	<0.012	<0.02	17400	73900
L/S = 5.0 - 10.0 l/kg	0.160	0.418	<0.00035	<0.017	51.5	3088	0.038	0.120	<0.015	<0.422	1945	37115	<2.5	<6.35	<0.02	<0.04	6200	80100

Sample Code	Mo mg/kg		Ni mg/kg		Pb mg/kg		Phenol mg/kg		Sb mg/kg		Se mg/kg		SO4 mg/kg		Zn mg/kg		NH3 mg/kg (as N)	
REP 2	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.010	0.010	0.098	0.098	0.055	0.055	6.00	6.00	0.003	0.003	<0.0009	<0.0009	125	125	0.578	0.578	91.3	91.3
L/S = 0.1 - 0.2 l/kg	0.008	0.018	0.082	0.180	0.039	0.093	5.40	11.4	0.002	0.005	<0.0009	<0.0018	107	232	0.481	1.06	81.0	172
L/S = 0.2 - 0.5 l/kg	0.020	0.038	0.211	0.391	0.077	0.170	18.6	30.0	0.005	0.010	<0.0027	<0.0045	315	547	1.12	2.18	199	371
L/S = 0.5 - 1.0 l/kg	0.027	0.064	0.327	0.718	0.087	0.257	22.5	52.5	0.011	0.021	<0.0045	<0.009	630	1177	1.62	3.79	312	683
L/S = 1.0 - 2.0 l/kg	0.027	0.091	0.394	1.11	0.062	0.319	14.4	66.9	0.012	0.033	<0.009	<0.018	1070	2247	1.92	5.71	397	1080
L/S = 2.0 - 5.0 l/kg	0.036	0.127	0.402	1.51	<0.003	<0.322	41.4	108	<0.03	<0.063	<0.027	<0.045	1356	3603	1.03	6.74	423	1503
L/S = 5.0 - 10.0 l/kg	0.060	0.187	0.187	1.70	0.008	<0.330	25.8	134	<0.05	<0.113	<0.045	<0.09	750	4353	0.570	7.31	72.0	1575

Reported by :

John Dunning
Test Area Manager

Date of Report: 16/04/03   Report Page 2 of 2

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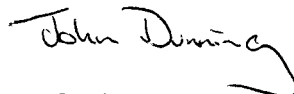
WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	
Company	Golder Associates	
Client Reference	DANO MSW	
WRc-NSF Reference	N18955/N19124	

Number of Samples Received	5
Date Samples Received	17/02/03
Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Contract Number	13113-0

Sample Code	As mg/l	Cd mg/l	Cl mg/l	Cr mg/l	Cu mg/l	DOC mg/l C	F mg/l	Hg mg/l	Mo mg/l	Ni mg/l	Pb mg/l	Phenol mg/l	Sb mg/l	Se mg/l	SO4 mg/l	Zn mg/l	NH3 mg/l N	TDS mg/l	pH -
REP 3																			
L/S = 0.0 - 0.1 l/kg	0.207	0.019	2720	0.079	1.51	30000	2.0	<0.004	0.287	0.983	0.878	82.0	0.030	<0.009	1190	12.8	1200	58800	5.76
L/S = 0.1 - 0.2 l/kg	0.169	0.014	1840	0.064	1.15	22200	2.0	<0.004	0.224	0.773	0.480	94.0	0.026	<0.009	1080	8.82	807	41600	5.76
L/S = 0.2 - 0.5 l/kg	0.156	0.012	1730	0.059	1.11	22300	1.5	<0.004	0.206	0.706	0.446	48.0	0.026	<0.009	1070	8.52	775	43200	5.73
L/S = 0.5 - 1.0 l/kg	0.134	0.009	1590	0.060	0.901	18400	1.0	<0.004	0.190	0.648	0.255	39.5	0.021	<0.009	1260	6.20	630	30900	5.61
L/S = 1.0 - 2.0 l/kg	0.093	0.005	1110	0.039	0.494	11800	1.0	<0.004	0.117	0.429	0.116	30.6	0.014	<0.009	1120	4.15	424	24300	5.57
L/S = 2.0 - 5.0 l/kg	0.032	0.0005	216	0.026	0.051	3040	0.5	<0.004	0.029	0.119	0.004	11.7	<0.01	<0.009	519	0.871	103	6200	6.00
L/S = 5.0 - 10.0 l/kg	0.028	0.0001	12.7	0.016	0.016	449	0.50	<0.004	0.014	0.026	0.002	3.70	<0.01	<0.009	123	0.144	9.70	1200	6.50

	As	Cd	Cl	Cr	Cu	DOC	F	Hg	Mo	Ni	Pb	Phenol	Sb	Se	SO4	Zn	NH3	TDS	pH
Prepn Ref	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14407	prEN14405
Method Ref	ING113	ING113	ING25$	ING113	ING113	ING52	$	ING75	ING113	ING113	ING113	$	ING95	ING113	ING25$	ING28	ING24	ING90	ING85
Run date	06/04/03	06/04/03	01/04/03	06/04/03	06/04/03	12/03/03	13/04/03	21/03/03	06/04/03	06/04/03	06/04/03	11/04/03	04/04/03	06/04/03	01/04/03	16/04/03	19/03/03	16/04/03	06/03/03

Reported by :

John Dunning
Test Area Manager

Date of Report: 16/04/03   Report Page 1 of 2

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WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	Number of Samples Received	5
Company	Golder Associates	Date Samples Received	17/02/03
Client Reference	DANO MSW	Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Reference	N18955/N19124	WRc-NSF Contract Number	13113-0

Sample Code	As mg/kg		Cd mg/kg		Cl mg/kg		Cr mg/kg		Cu mg/kg		DOC mg/kg		F mg/kg		Hg mg/kg		TDS mg/kg	
REP 3	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.021	0.021	0.0019	0.002	272	272	0.008	0.008	0.151	0.151	3000	3000	<0.2	<0.2	<0.0004	<0.0004	5880	5880
L/S = 0.1 - 0.2 l/kg	0.017	0.038	0.0014	0.003	184	456	0.006	0.014	0.115	0.266	2220	5220	<0.2	<0.4	<0.0004	<0.0008	4160	10040
L/S = 0.2 - 0.5 l/kg	0.047	0.084	0.0036	0.007	519	975	0.018	0.032	0.333	0.599	6690	11910	<0.45	<0.85	<0.0012	<0.002	12960	23000
L/S = 0.5 - 1.0 l/kg	0.067	0.151	0.0044	0.011	795	1770	0.030	0.062	0.451	1.05	9200	21110	<0.5	<1.35	<0.002	<0.004	15450	38450
L/S = 1.0 - 2.0 l/kg	0.093	0.244	0.0048	0.016	1110	2880	0.039	0.101	0.494	1.54	11800	32910	<1.0	<2.35	<0.004	<0.008	24300	62750
L/S = 2.0 - 5.0 l/kg	0.097	0.341	0.0014	0.017	648	3528	0.077	0.177	0.153	1.70	9120	42030	<1.5	<3.85	<0.012	<0.02	18600	81350
L/S = 5.0 - 10.0 l/kg	0.139	0.480	0.0004	0.018	63.5	3592	0.080	0.257	0.081	1.78	2245	44275	<2.5	<6.35	<0.02	<0.04	6000	87350

	Mo mg/kg		Ni mg/kg		Pb mg/kg		Phenol mg/kg		Sb mg/kg		Se mg/kg		SO4 mg/kg		Zn mg/kg		NH3 mg/kg (as N)	
REP 3	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.029	0.029	0.098	0.098	0.088	0.088	8.20	8.20	0.003	0.003	<0.0009	<0.0009	119	119	1.28	1.280	120	120
L/S = 0.1 - 0.2 l/kg	0.022	0.051	0.077	0.176	0.048	0.136	9.40	17.6	0.003	0.006	<0.0009	<0.0018	108	227	0.882	2.162	80.7	201
L/S = 0.2 - 0.5 l/kg	0.062	0.113	0.212	0.387	0.134	0.270	14.4	32.0	0.008	0.013	<0.0027	<0.0045	321	548	2.556	4.72	233	433
L/S = 0.5 - 1.0 l/kg	0.095	0.208	0.324	0.711	0.128	0.397	19.8	51.8	0.011	0.024	<0.0045	<0.009	630	1178	3.1	7.82	315	748
L/S = 1.0 - 2.0 l/kg	0.117	0.325	0.429	1.14	0.116	0.513	30.6	82.4	0.014	0.038	<0.009	<0.018	1120	2298	4.15	11.97	424	1172
L/S = 2.0 - 5.0 l/kg	0.087	0.412	0.357	1.50	0.013	0.526	35.1	117	<0.03	<0.068	<0.027	<0.045	1557	3855	2.613	14.58	309	1481
L/S = 5.0 - 10.0 l/kg	0.072	0.483	0.131	1.63	0.011	0.537	18.5	136	<0.05	<0.118	<0.045	<0.09	615	4470	0.72	15.30	48.5	1530

Reported by :

John Dunning
Test Area Manager

Date of Report: 16/04/03   Report Page 2 of 2

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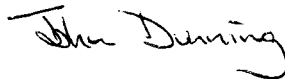
WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury
Company	Golder Associates
Client Reference	DANO MSW
WRc-NSF Reference	N18955/N19124

Number of Samples Received	5
Date Samples Received	17/02/03
Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Contract Number	13113-0

Sample Code	As mg/l	Cd mg/l	Cl mg/l	Cr mg/l	Cu mg/l	DOC mg/l C	F mg/l	Hg mg/l	Mo mg/l	Ni mg/l	Pb mg/l	Phenol mg/l	Sb mg/l	Se mg/l	SO4 mg/l	Zn mg/l	NH3 mg/l N	TDS mg/l	pH -
REP 4																			
L/S = 0.0 - 0.1 l/kg	0.309	0.032	3420	0.102	2.20	38300	<2.0	<0.004	0.405	1.46	1.77	96.0	0.038	<0.009	1370	17.6	1230	78600	5.54
L/S = 0.1 - 0.2 l/kg	0.278	0.030	3240	0.090	2.51	34800	<2.0	<0.004	0.380	1.33	1.54	98.0	0.034	<0.009	1280	15.3	1170	65200	5.56
L/S = 0.2 - 0.5 l/kg	0.177	0.018	1990	0.061	1.55	23000	<1.5	<0.004	0.250	0.914	0.772	84.0	0.026	<0.009	1090	10.2	859	48800	5.57
L/S = 0.5 - 1.0 l/kg	0.149	0.015	1930	0.051	1.12	20200	<1.0	<0.004	0.223	0.818	0.533	58.0	0.021	<0.009	1120	8.70	745	40300	5.63
L/S = 1.0 - 2.0 l/kg	0.101	0.006	1310	0.105	0.514	13600	<1.0	<0.004	0.139	0.575	0.227	33.8	0.014	<0.009	1010	5.40	466	26600	5.60
L/S = 2.0 - 5.0 l/kg	0.041	0.001	233	0.008	0.083	3550	<0.5	<0.004	0.029	0.147	0.021	13.3	<0.01	<0.009	508	1.15	113	7280	5.76
L/S = 5.0 - 10.0 l/kg	0.036	<0.00007	10.8	0.037	0.019	501	<0.5	<0.004	<0.012	0.044	<0.0001	5.15	<0.01	<0.009	138	0.203	9.54	1240	6.37

	As	Cd	Cl	Cr	Cu	DOC	F	Hg	Mo	Ni	Pb	Phenol	Sb	Se	SO4	Zn	NH3	TDS
Prepn Ref	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14407	prEN14405
Method Ref	ING113	ING113	ING25$	ING113	ING113	ING52	$	ING75	ING113	ING113	ING113	$	ING95	ING113	ING25$	ING28	ING24	ING90	ING85
Run date	06/04/03	06/04/03	01/04/03	06/04/03	06/04/03	12/03/03	13/04/03	21/03/03	06/04/03	06/04/03	06/04/03	11/04/03	04/04/03	06/04/03	01/04/03	16/04/03	19/03/03	16/04/03	06/03/03

Reported by :

John Dunning

John Dunning

Test Area Manager

Date of Report: 16/04/03

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WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	
Company	Golder Associates	
Client Reference	DANO MSW	
WRc-NSF Reference	N18955/N19124	

Number of Samples Received	5	
Date Samples Received	17/02/03	
Sample Types	prEN 14405 Leach Test Extract	
WRc-NSF Contract Number	13113-0	

Sample Code	As mg/kg		Cd mg/kg		Cl mg/kg		Cr mg/kg		Cu mg/kg		DOC mg/kg		F mg/kg		Hg mg/kg		TDS mg/kg	
REP 4	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.031	0.031	0.0032	0.003	342	342	0.010	0.010	0.220	0.220	3830	3830	<0.2	<0.2	<0.0004	<0.0004	7860	7860
L/S = 0.1 - 0.2 l/kg	0.028	0.059	0.0030	0.006	324	666	0.009	0.019	0.251	0.471	3480	7310	<0.2	<0.4	<0.0004	<0.0008	6520	14380
L/S = 0.2 - 0.5 l/kg	0.053	0.112	0.0055	0.012	597	1263	0.018	0.037	0.465	0.936	6900	14210	<0.45	<0.85	<0.0012	<0.002	14640	29020
L/S = 0.5 - 1.0 l/kg	0.075	0.186	0.0076	0.019	965	2228	0.026	0.063	0.560	1.50	10100	24310	<0.5	<1.35	<0.002	<0.004	20150	49170
L/S = 1.0 - 2.0 l/kg	0.101	0.287	0.0059	0.025	1310	3538	0.105	0.168	0.514	2.01	13600	37910	<1.0	<2.35	<0.004	<0.008	26600	75770
L/S = 2.0 - 5.0 l/kg	0.123	0.410	0.0038	0.029	699	4237	0.023	0.191	0.248	2.26	10650	48560	<1.5	<3.85	<0.012	<0.02	21840	97610
L/S = 5.0 - 10.0 l/kg	0.179	0.589	<0.00035	0.029	54.0	4291	0.187	0.378	0.093	2.35	2505	51065	<2.5	<6.35	<0.02	<0.04	6200	103810

	Mo mg/kg		Ni mg/kg		Pb mg/kg		Phenol mg/kg		Sb mg/kg		Se mg/kg		SO4 mg/kg		Zn mg/kg		NH3 mg/kg (as N)	
REP 4	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.041	0.041	0.146	0.146	0.177	0.177	9.60	9.60	0.004	0.004	<0.0009	<0.0009	137	137	1.76	1.76	123	123
L/S = 0.1 - 0.2 l/kg	0.038	0.079	0.133	0.279	0.154	0.331	9.80	19.4	0.003	0.007	<0.0009	<0.0018	128	265	1.53	3.29	117	240
L/S = 0.2 - 0.5 l/kg	0.075	0.154	0.274	0.553	0.232	0.563	25.2	44.6	0.008	0.015	<0.0027	<0.0045	327	592	3.06	6.35	258	498
L/S = 0.5 - 1.0 l/kg	0.112	0.265	0.409	0.962	0.267	0.829	29.0	73.6	0.010	0.025	<0.0045	<0.009	560	1152	4.35	10.7	373	870
L/S = 1.0 - 2.0 l/kg	0.139	0.404	0.575	1.54	0.227	1.06	33.8	107	0.014	0.039	<0.009	<0.018	1010	2162	5.40	16.1	466	1336
L/S = 2.0 - 5.0 l/kg	0.086	0.490	0.441	1.98	0.062	1.12	39.9	147	<0.03	<0.069	<0.027	<0.045	1524	3686	3.45	19.6	339	1675
L/S = 5.0 - 10.0 l/kg	0.060	0.550	0.221	2.20	<0.0005	1.12	25.8	173	<0.05	<0.119	<0.045	<0.09	690	4376	1.02	20.6	47.7	1723

Reported by:

John Dunning
Test Area Manager

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Opinions and interpretations expressed herein are outside the scope of UKAS Accreditation
Details of the WRc-NSF UKAS Accreditation Schedule are available on request.
Samples were analysed as received unless otherwise stated.

Tests marked $: Not included in the WRc-NSF UKAS Accreditation Schedule
Tests marked @ : Tests not performed by WRc-NSF. Approved subcontractor is not UKAS accredited for this test
Tests marked * : Tests not performed by WRc-NSF. Approved subcontractor is UKAS accredited for this test
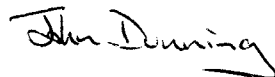
WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	Number of Samples Received	5
Company	Golder Associates	Date Samples Received	17/02/03
Client Reference	DANO MSW	Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Reference	N18955/N19124	WRc-NSF Contract Number	13113-0

Sample Code	As mg/l	Cd mg/l	Cl mg/l	Cr mg/l	Cu mg/l	DOC mg/l C	F mg/l	Hg mg/l	Mo mg/l	Ni mg/l	Pb mg/l	Phenol mg/l	Sb mg/l	Se mg/l	SO4 mg/l	Zn mg/l	NH3 mg/l N	TDS mg/l	pH -
REP 5																			
L/S = 0.0 - 0.1 l/kg	0.261	0.037	3010	0.066	1.43	32700	<2.0	<0.004	0.353	1.25	1.45	120	0.036	<0.009	1220	20.3	1094	69400	5.58
L/S = 0.1 - 0.2 l/kg	0.228	0.033	2490	0.085	1.21	29200	<2.0	<0.004	0.299	1.09	1.07	88.0	0.032	<0.009	1150	16.5	939	56000	5.55
L/S = 0.2 - 0.5 l/kg	0.199	0.024	2150	0.076	1.19	23200	<1.5	<0.004	0.272	0.943	0.706	36.0	0.031	<0.009	1120	14.3	771	47500	5.57
L/S = 0.5 - 1.0 l/kg	0.158	0.018	1800	0.056	0.737	16700	<1.0	<0.004	0.220	0.773	0.405	46.0	0.021	<0.009	1070	11.1	581	37300	5.55
L/S = 1.0 - 2.0 l/kg	0.106	0.009	1480	0.027	0.468	13100	<1.0	<0.004	0.137	0.506	0.182	34.8	0.018	<0.009	1020	7.19	425	26900	5.62
L/S = 2.0 - 5.0 l/kg	0.050	0.0019	256	0.005	0.124	4060	<0.5	<0.004	0.035	0.171	0.025	15.5	<0.01	<0.009	480	1.84	121	8280	5.73
L/S = 5.0 - 10.0 l/kg	0.029	<0.00007	12.2	<0.003	0.028	524	<0.5	<0.004	<0.012	0.043	0.002	6.65	<0.01	<0.009	159	0.274	11.8	1440	6.32

	As	Cd	Cl	Cr	Cu	DOC	F	Hg	Mo	Ni	Pb	Phenol	Sb	Se	SO4	Zn	NH3	TDS
Prepn Ref	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14405	prEN14407	prEN14405
Method Ref	ING113	ING113	ING25$	ING113	ING113	ING52	$	ING75	ING113	ING113	ING113	$	ING95	ING113	ING25$	ING28	ING24	ING90	ING85
Run date	06/04/03	06/04/03	01/04/03	06/04/03	06/04/03	12/03/03	13/04/03	21/03/03	06/04/03	06/04/03	06/04/03	11/04/03	04/04/03	06/04/03	01/04/03	16/04/03	19/03/03	16/04/03	06/03/03

Reported by :

John Dunning

John Dunning

Test Area Manager

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WRc-NSF Ltd

ANALYSIS REPORT

Contact Name	David Drury	Number of Samples Received	5
Company	Golder Associates	Date Samples Received	17/02/03
Client Reference	DANO MSW	Sample Types	prEN 14405 Leach Test Extract
WRc-NSF Reference	N18955/N19124	WRc-NSF Contract Number	13113-0

Sample Code	As mg/kg		Cd mg/kg		Cl mg/kg		Cr mg/kg		Cu mg/kg		DOC mg/kg		F mg/kg		Hg mg/kg		TDS mg/kg	
REP 5	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.026	0.026	0.0037	0.004	301	301	0.007	0.007	0.143	0.143	3270	3270	<0.2	<0.2	<0.0004	<0.0004	6940	6940
L/S = 0.1 - 0.2 l/kg	0.023	0.049	0.0033	0.007	249	550	0.009	0.015	0.121	0.264	2920	6190	<0.2	<0.4	<0.0004	<0.0008	5600	12540
L/S = 0.2 - 0.5 l/kg	0.060	0.109	0.0073	0.014	645	1195	0.023	0.038	0.357	0.621	6960	13150	<0.45	<0.85	<0.0012	<0.002	14250	26790
L/S = 0.5 - 1.0 l/kg	0.079	0.188	0.0089	0.023	900	2095	0.028	0.066	0.369	0.990	8350	21500	<0.5	<1.35	<0.002	<0.004	18650	45440
L/S = 1.0 - 2.0 l/kg	0.106	0.294	0.0088	0.032	1480	3575	0.027	0.093	0.468	1.46	13100	34600	<1.0	<2.35	<0.004	<0.008	26900	72340
L/S = 2.0 - 5.0 l/kg	0.149	0.443	0.0056	0.038	768	4343	0.015	0.108	0.372	1.83	12180	46780	<1.5	<3.85	<0.012	<0.02	24840	97180
L/S = 5.0 - 10.0 l/kg	0.143	0.586	0.0004	0.038	61.0	4404	<0.015	<0.123	0.138	1.97	2620	49400	<2.5	<6.35	<0.02	<0.04	7200	104380

Sample Code	Mo mg/kg		Ni mg/kg		Pb mg/kg		Phenol mg/kg		Sb mg/kg		Se mg/kg		SO4 mg/kg		Zn mg/kg		NH3 mg/kg (as N)	
REP 5	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative	Fraction	Cumulative
L/S = 0.0 - 0.1 l/kg	0.035	0.035	0.125	0.125	0.145	0.145	12.0	12.0	0.004	0.004	<0.0009	<0.0009	122	122	2.03	2.03	109	109
L/S = 0.1 - 0.2 l/kg	0.030	0.065	0.109	0.234	0.107	0.252	8.80	20.8	0.003	0.007	<0.0009	<0.0018	115	237	1.65	3.68	93.9	203
L/S = 0.2 - 0.5 l/kg	0.082	0.147	0.283	0.517	0.212	0.464	10.8	31.6	0.009	0.016	<0.0027	<0.0045	336	573	4.29	7.97	231	435
L/S = 0.5 - 1.0 l/kg	0.110	0.257	0.387	0.903	0.203	0.666	23.0	54.6	0.011	0.027	<0.0045	<0.009	535	1108	5.55	13.5	291	725
L/S = 1.0 - 2.0 l/kg	0.137	0.394	0.506	1.41	0.182	0.848	34.8	89.4	0.018	0.044	<0.009	<0.018	1020	2128	7.19	20.7	425	1150
L/S = 2.0 - 5.0 l/kg	0.106	0.500	0.513	1.92	0.075	0.923	46.5	136	<0.03	<0.074	<0.027	<0.045	1440	3568	5.52	26.2	363	1513
L/S = 5.0 - 10.0 l/kg	<0.06	<0.560	0.216	2.14	0.011	0.934	33.3	169	<0.05	<0.124	<0.045	<0.09	795	4363	1.37	27.6	59.0	1572

Reported by :

John Dunning

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Test Area Manager

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Part C

Comparison of LandSim 2.02 with LandSim 2.5

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1.0 Introduction

1.1 Background to this report

An assessment of the risks to groundwater quality is required of landfills regulated under the PPC Regulations 2000 or Waste Management Licensing Regulations 1994.

A sophisticated way of simulating the change in landfill leachate quality with time was developed during negotiations with the EU Technical Adaptation Committee dealing with Annex 2 of the Landfill Directive to derive waste acceptance criteria.

In light of the Landfill Directive's requirements for the risks to the environment throughout the lifetime of the site to be taken into account, the Environment Agency's Landfill Directive Regulatory Guidance Note 6 states: "The risk assessment must take account of future failure and degradation of the active controls (e.g. artificial sealing liner and leachate drainage systems, and operational/management controls) as well as the likely contaminant concentrations in the landfill when failure/degradation occurs".

The Environment Agency therefore requested LandSim, to be upgraded, from version 2.02 to version 2.5, so that account can be taken of recent developments in the simulation of leachate quality and of failure and degradation of active controls.

1.2 Purpose and aims of the report

The purpose of this report is to compare the predictions of LandSim 2.5 with the existing version of LandSim (version 2.02).

1.3 Report structure

Section 2 follows this introduction and describes the approach that was taken to the comparison exercise. Results of the exercise are presented in Section 3. The difference in the predictions between LandSim 2.02 and LandSim 2.5 are discussed in Section 4.

2.0 Methodology for the comparison exercise

The predictions of the two versions of LandSim were compared by simulating the migration of four common leachate constituents from a landfill engineered to a typical UK specification. The four leachate constituents were chosen to represent the diversity of behaviours of contaminants in the landfill and geological environments.

LandSim 2.5 is still being coded at the time of preparation of this document. However, the concepts behind the development of the model were developed and tested in a simulation environment called 'GoldSim'. The GoldSim version of LandSim 2.5 is deterministic and has been used in this exercise. Table 1 lists all the parameters used by the LandSim 2.5 model and their values with justification.

The publicly available version of LandSim 2.02 was used in the exercise. Appendices 1 to 3 contain summaries of the model input parameters and values.

The comparison exercise considered six scenarios - three scenarios using LandSim 2.02 and three scenarios using LandSim 2.5. The three scenarios using LandSim 2.02 address the effect of changing the source term concentration and the three scenarios using LandSim 2.5 assess the effect of changing the duration of institutional/operational control.

Table 2 lists the scenarios.

Table 2: Scenarios addressed by the comparison exercise

LandSim 2.02 Scenarios	
Scenario 1	LandSim 2.02 range of leachate concentrations
Scenario 2	Proposed LandSim 2.5 range of leachate concentrations
Scenario 3	Single value of leachate concentration used in LandSim 2.5 model
LandSim 2.5 Scenarios	
Scenario 4	40 year period of institutional/operational control
Scenario 5	100 year period of institutional/operational control
Scenario 6	400 year period of institutional/operational control

The concentration ranges used in the three LandSim 2.02 scenarios are shown in Table 3. The toluene and mecoprop concentrations are the mean concentrations detected in a study of 63 leachate samples from 58 UK and Ireland landfills (Knox et al, 2000).

Table 3: Concentration ranges used in the LandSim 2.02 model scenarios

	Cadmium concentration (mg/l)	Chloride concentration (mg/l)	Toluene concentration (mg/l)	Mecoprop concentration (mg/l)
Scenario 1: LandSim 2.02 range of leachate concentrations	log triangular (0.0019, 0.0101, 0.105)	log triangular (36, 2270, 7760)	single value (0.087)	single value (0.0218)
Scenario 2: Proposed LandSim 2.5 range of leachate concentrations	log triangular (0.0019, 0.0101, 0.105)	log triangular (227, 997, 2650)	single value (0.087)	single value (0.0218)
Scenario 3: Single value of leachate concentration used in LandSim 2.5 model	single value (0.0101)	single value (2270)	single value (0.087)	single value (0.0218)

Table 1: List of all parameters used by the LandSim 2.5 model and their values with justification

Contaminants and materials

GoldSim data element	Explanation	Value	Comment
Diffusivity of contaminants in water	Diffusivity of contaminants in water.	1×10^{-9} m2/s	
Aquifer water partition coefficients		Cl =0 l/kg Cd = 20 l/kg Toluene = 0.29 l/kg Mecoprop = 0.02 l/kg	
Liner water partition coefficients		Cl =0 l/kg Cd = 20 l/kg Toluene = 0.29 l/kg Mecoprop = 0.02 l/kg	
initial_conc	Initial leachate concentration.	Cl = 2270 mg/l Cd = 10.1 µg/l Toluene = 87 µg/l Mecoprop = 21.8 µg/l	Chloride and cadmium are the most likely values from LandSim. Toluene and mecoprop are the mean values from Knox et al, 2000
kappa_slope	Used with kappa intercept and the initial concentration to define the value of kappa describes the rate of release from waste into leachate.	Cl = 0.0298 kg/l Cd = 0.0823 kg/l Toluene = 0 kg/l Mecoprop = 0.0298kg/l	Chloride and cadmium from the scoping study. Toluene is volatile. In the absence of data, mecoprop is assigned the same values as chloride
kappa_intercept	Used with kappa slope and the initial concentration to define the value of kappa describes the rate of release from waste into leachate.	Cl = 0.2919 kg/l Cd = 0.1589 kg/l Toluene = 0 kg/l Mecoprop = 0.2919 kg/l	Chloride and cadmium from the scoping study. Toluene is volatile. In the absence of data, mecoprop is assigned the same values as chloride
volatile species half life	Used to define the change in concentration of volatile species in the source term.	10 year	Value recommended by scoping study. Used for toluene
biodegradation half life	Defines the biodegradation half life in the mineral liner, unsaturated pathway and saturated pathway.	Mecoprop = 1 year	Mecoprop value from "The effects of contaminant concentration on the potential for natural attenuation" R&D Technical report P2-228/TR. Value for aerobic biodegradation in shallow sand/gravel aquifer

Table 1: continued

Geometry

GoldSim data element	Explanation	Value	Comment
cell_width		200 m	
cell_length		200 m	
waste_thickness		20 m	
level_sw_breakout	Elevation above the base of the site which surface water breakout occurs.	20 m	
waste_density		1000 kg/m^3	
waste_porosity		0.4	
waste_field_capacity		0.3	
surface_area		60,000 m^2	

Timing and institutional control

GoldSim data element	Explanation	Value	Comment
landfilling_duration		10 yr	
duration_institutional_control	Duration of institutional and operational control.	30 yr	The time following landfilling when the cap degrades, leachate is no longer pumped to a treatment plant, leachate recirculation ends and leachate head is therefore no longer fixed

Cap

GoldSim data element	Explanation	Value	Comment
cap_infiltration	The infiltration to the landfill cap before any degradation occurs.	50 mm/yr	
grassland_infiltration	The infiltration to grassland in the vicinity of the landfill.	140 mm/yr	
time_of_cap_deg_onset	The time since landfilling commenced when FML caps start to degrade.	250 yr	
time_of_total_cap_degradation	The time since landfilling commenced when the degradation of FML caps results in the infiltration being that through grassland in the vicinity of the landfill.	1,000 yr	

Hydraulics

GoldSim data element	Explanation	Value	Comment
proposed_permitted_head	The leachate head during operational/institutional control.	1 m	
rainfall_to_waste	Infiltration of rainfall to waste prior to capping.	250 mm/yr	
recirculation_rate	The rate of leachate recirculation.	50 mm/yr	

Liner

GoldSim data element	Explanation	Value	Comment
area_pinhole	The area of a pinhole defect in a FML liner.	2.55 mm^2	Average of LandSim minimum and maximum values
area_hole	The area of a hole defect in a FML liner.	52.5 mm^2	Average of LandSim minimum and maximum values
area_tear	The area of a tear defect in a FML liner.	5050 mm^2	Average of LandSim minimum and maximum values
contact_coefficient	Contact coefficient for calculation of leakage through FML liner.	1.05	Contact coefficient used in LandSim for leakage calculations
contact_coefficient_r	Contact coefficient for calculation of radius of area of leakage through FML liner.	0.45	Contact coefficient used in LandSim for calculation of radius
number_pinhole_start	The initial (design) number of pinholes in a FML liner	0 ha^{-1}	
number_hole_start	The initial (design) number of holes in a FML liner.	0 ha^{-1}	
number-tear_start	The initial (design) number of tears in a FML liner.	0 ha^{-1}	
number_hole_end	The number of holes at the end of the period of institutional control.	5 ha^{-1}	
number_pinhole_end	The number of pinholes at the end of the period.	5 ha^{-1}	
number_tear_end	The number of tears at the end of the period of institutional control.	0.1 ha^{-1}	
clay_permeability	The permeability of the mineral part of a liner.	1 x 10^{-9} m/s	
mineral_liner_porosity	Porosity of clay liner.	0.3	

Table 1: Continued

Liner - continued

GoldSim data element	Explanation	Value	Comment
mineral_liner_density	Density of clay liner	1800 kg/m^3	
onset_of_fml_degradation	Time since start of landfilling of the onset of degradation of a FML artificial sealing liner.	150 yrs	
liner_thickness	Thickness of mineral part of liner.	1 m	
degradation_half_life	The rate of degradation of the area of defects in an FML artificial sealing liner.	100 yrs	

Unsaturated zone

GoldSim data element	Explanation	Value	Comment
thickness_uz	Unsaturated zone thickness.	5 m	

Saturated zone

GoldSim data element	Explanation	Value	Comment
distance_to_receptor_1		10 m	
distance_to_receptor_2		200 m	
darcy_flux	Darcy flux in the saturated zone. The product of hydraulic conductivity and hydraulic gradient.	15 m/yr	
aquifer_porosity	Moisture content of the unsaturated zone and porosity of the saturated zone.	0.3	
aquifer_thickness	Thickness of the saturated zone.	5 m	
aquifer_density	Density of the unsaturated and saturated zone.	2000 kg/m^3	

3.0 Results of the comparison exercise

The predictions of the LandSim 2.02 models are shown in Figure 1 to Figure 3. The predictions of the GoldSim (LandSim 2.5) model are shown in Figure 4 and Figure 5.

3.1   Results of the LandSim 2.02 scenarios

The leakage of leachate from the landfill site was unaffected by the different source concentrations.

The peak concentration of toluene was reduced during its migration through the unsaturated zone by dispersion combined with partition to unsaturated zone material. The peak concentration was greater than the minimum reporting value (Environment Agency, 2003), 4 µg/l, at all the levels of confidence shown in Figure 1.

The concentration of mecoprop in the leachate was predicted to become lower during its passage through the unsaturated zone because of the process of biodegradation. The peak concentration at the base of the unsaturated zone was less than the minimum reporting value, 0.04 µg/l, even at the 99% confidence level.

The predicted concentration of chloride at the receptor downgradient of the landfill was similar using the LandSim 2.02 range of concentration (Scenario 1) and the single value used in the GoldSim LandSim 2.5 model (Scenario 3).   The effect of averaging the spot measurements of chloride concentration to produce an average, or bulk, leachate concentration reduces the range of the distribution. The predicted chloride concentration was therefore less at higher percentiles although the predicted 50%ile concentration in Scenario 1 and Scenario 2 was very similar (Figure 2).

The range of cadmium concentrations in leachate predicted in LandSim 2.02 was wide. The single value used in the GoldSim LandSim 2.5 model is the most likely of the log triangular distribution but this is towards the low end of the range. However, except at low levels of confidence using the LandSim 2.02 range of cadmium concentrations, the effect of dispersion combined with equilibrium partitioning is not enough to reduce the peak concentration at the base of the unsaturated zone to below the minimum reporting value (Environment Agency, 2003), 0.1 µg/l.   The predicted concentration at the base of the unsaturated zone at the 50% confidence level is similar for both cadmium scenarios. The spread in predicted peak concentration using the LandSim 2.02 source concentration is due to the variability in the leachate concentration (Figure 3).

3.2   Results of the GoldSim (LandSim 2.5) scenarios

The infiltration to the landfill site is unaffected by the duration of institutional/operational control. When institutional/operational control is lost, then the head of leachate is predicted to rise rapidly because infiltration to the waste exceeds the predicted leakage through the basal liner. The highest leachate level is reached when the cap degradation is advanced yet the basal liner has not fully degraded. The difference in surface water breakout between the scenarios is negligible although a shorter duration of institutional/operational control results in a predicted short duration of surface water breakout when infiltration is relatively high before the liner degradation is far advanced. Flow to off-site disposal is predicted to be greater for longer periods of institutional/operational control, and if institutional/operational control is maintained beyond the time of onset of the cap degradation, then flow to off-site disposal is predicted to have to increase. Leakage from the landfill is a direct response to the predicted leachate head. It rises rapidly following the cessation of institutional/operational control and stays high, despite a falling leachate head, because the integrity of the basal liner is reduced (Figure 4).

On the timescale of the life of the landfill the differences in the change in leachate concentration with different durations of institutional/operational control do not appear to be significant. However, at any time the concentration of a non-volatile species is predicted to be much lower if

institutional/operational control is maintained for longer because considerably more mass of contaminant is removed from the waste for off-site disposal.

The concentration in leachate of toluene, a volatile contaminant, is not discernibly affected by the duration of institutional/operational control, because its removal from the landfill is almost complete by the time management control is assumed to end.

The removal of contaminant mass to off-site disposal means the predicted cadmium and mecoprop concentration is lower at the base of the unsaturated zone if institutional/ operational control is maintained for longer. However, even with a period of 400 years institutional/operational control, the predicted peak concentration of cadmium exceeds the minimum reporting value (Environment Agency, 2003) of 0.1 µg/l.

The process of biodegradation in the unsaturated zone mitigates the predicted impact of mecoprop at the water table. A longer travel time through the unsaturated zone therefore reduces the predicted peak concentration at the base of the unsaturated zone. A lower leakage rate, as a result of maintaining institutional/operational control for longer, therefore results in a reduced impact.

Whilst most of the toluene mass in the landfill is removed via volatilisation, a portion of the total mass will partition into the leachate and be transported from the landfill via the liner. Once toluene has leaked from the landfill, its concentration at the water table is reduced by equilibrium partitioning combined with dispersion in the unsaturated zone. However, the predicted peak concentration slightly exceeds the minimum reporting value (Environment Agency, 2003) and is independent of the duration of institutional/operational control. This is because most of the mass of toluene is transported from the landfill before the earliest assumed loss of institutional/operational control. The predicted concentrations with 100 and 400 years institutional/operational control are the same because the effect of release of toluene from the landfill is almost over after 100 years. The predicted concentrations following peak impact for 40 years institutional/operational control are less than those predicted for greater durations of institutional/operational control. The predicted concentrations are underestimates and reflect a limitation of the Laplace transformation approach used to solve the advection dispersion equation.

The predicted concentration of chloride at the saturated zone receptor is just below the maximum admissible concentration in UK drinking water if the duration of institutional/ operational control is extended to 100 years. It is comfortably below the maximum admissible concentration in UK drinking water if institutional/operational control lasts for 400 years. Extending institutional/operational control delays the timing of the peak impact (which occurs as a result of the high rate of leakage that is predicted to occur once the leachate head rises as institutional/operational control is lost) until the leachate is weaker.

4.0 Discussion of the differences between Landsim 2.02 and Landsim 2.5

The predicted leakage rate in the GoldSim LandSim 2.5 model, when the leachate head is maintained at 1 m, is very similar to the leakage rate predicted by the LandSim 2.02 model.

The decline in concentration of toluene in leachate predicted by LandSim 2.5 suggests that volatile species will be removed from the leachate more rapidly than predicted by the LandSim 2.02 model. For example, toluene concentration was predicted to have declined to near zero in approximately 50 years in the LandSim 2.5 model whereas it was predicted to take 1,000 years in the LandSim 2.02 model. As a result, LandSim 2.5 is likely to predict much lower concentrations of volatile contaminants at the water table than LandSim 2.02. In this example, LandSim 2.02 predicted that the landfill would have allowed an unacceptable discharge of toluene to the water table, whereas LandSim 2.5 predicted the peak concentration to be close to the minimum reporting value.

The leachate was predicted to stay stronger with respect to mecoprop with LandSim 2.5 than with LandSim 2.02, although the concentration at any time is in the same order of magnitude. However, in the absence of data, the parameters that are used to define the kappa value ('kappa slope' and 'kappa intercept') in the LandSim 2.5 model have been assumed to be the same as chloride. The calculated kappa value using these parameters, is similar to that calculated for cadmium as a result of mecoprop having a lower initial concentration than chloride in the leachate. The predicted concentration of mecoprop at the water table is predicted to be acceptable with either version of LandSim, although the predicted concentration with LandSim 2.5 is approximately one order of magnitude higher. This is as a result of a combination of the stronger source and higher leakage rates.

The predicted concentration of chloride in the leachate by both models is similar. This is because the declining source in LandSim 2.02 implicitly assumes the contaminants are in the aqueous phase from the start of a simulation. The phase distribution of contaminants is better represented by the kappa driven declining source term in LandSim 2.5. In the case of a mobile species like chloride, the LandSim 2.02 assumption is probably reasonable and therefore the rate of change of concentration is likely to be similar to that predicted by LandSim 2.5. The predicted chloride concentration in the saturated zone is lower with LandSim 2.02 than LandSim 2.5 because of the lower predicted leakage rates over the life of the site. The results from the LandSim 2.02 scenarios suggest that the calculation of an average initial concentration from spot measurement data in LandSim 2.5 will reduce the predicted peak impact of chloride at the water table by a little less than a half.

LandSim 2.02 predicted cadmium concentrations at the base of the unsaturated zone are much lower because the reduced leakage rate increases travel time and thereby increases the effect of the processes of equilibrium partitioning and dispersion. Neither model predicted that the discharge to the water table would be acceptable. However, the models assumed that the clay component of the lining system only just achieved the maximum permeability specification (1×10^{-9} m/s). The permeability of as-built clay liners can often be justified to be considerably less than this value and would permit the leakage of much less leachate than predicted from the landfill considered in this exercise. The reduction in leakage through a lower permeability liner is balanced to a certain degree by an increased leachate head, when institutional/operational control ends, which results in greater leakage. The consequence of higher leachate heads following cessation of institutional/operational control of sites constructed with lower permeability liners is also to increase the likelihood of leachate breakout at the ground surface.

5.0 Conclusions of the study

This exercise has compared the predictions of a development version of LandSim 2.5 with the existing LandSim version 2.02.

Of the changes to the source term, it is the proposed change to the rate of change in concentration of volatile contaminants in leachate that is the most significant. The new version of LandSim will predict much more rapid reduction in the leachate concentration of volatile contaminants, and therefore lower concentrations at the water table. The proposed changes to the way that the initial concentration of species not on List I is calculated, and the way that the change in concentration of non-volatile species will be simulated are considered to add realism to the model, but not to have dramatic effects on predictions.

LandSim 2.5 will allow the simulation of degradation of engineering and cessation of institutional/operational control. It is the simulation of the ending of institutional/operational control that has the most pronounced effect on the changes in predicted concentration. It is likely to result in higher predicted concentrations of mobile species and those contaminants whose effects at receptors are mitigated by processes, such as biodegradation, that rely on extended travel times.

6.0 References

Knox, K., Robinson, H. D., van Santen, A., and Tempany, P. R., October 2000. *The occurrence of trace organic components in landfill leachates and their removal during on-site treatment*. Proceedings Waste 2000, Waste Management at the dawn of the third Millennium. Stratford-upon-Avon, Warwickshire, England; 2-4 October 2000.
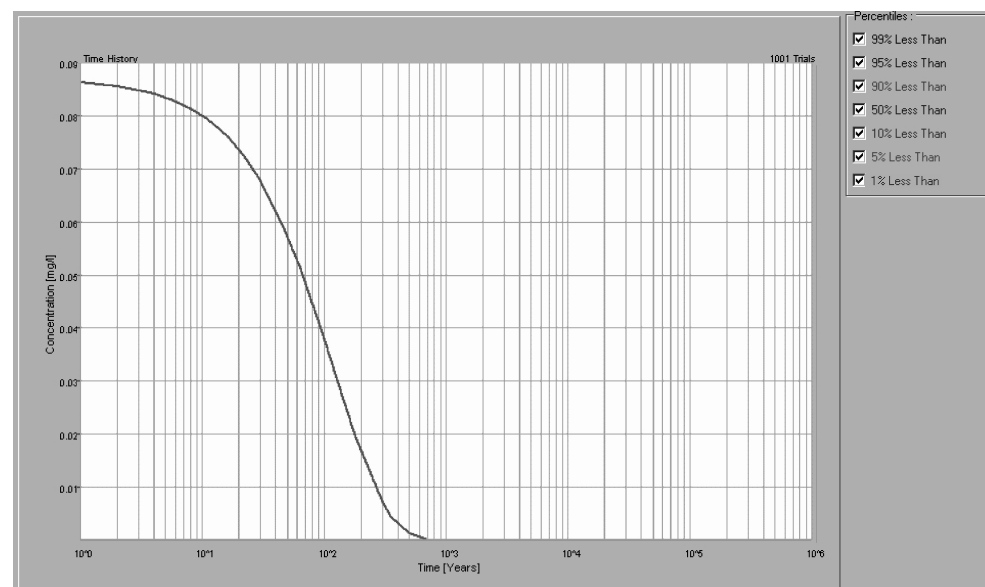
Environment Agency, 2003. *Hydrogeological risk assessments for landfills and the derivation of groundwater control and trigger levels*. Environment Agency, Bristol.
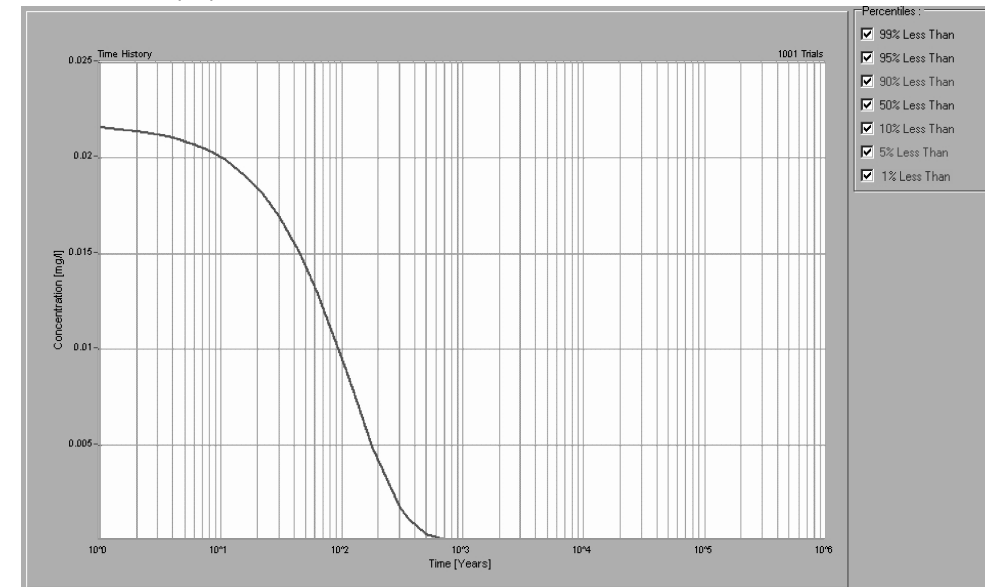
Figures

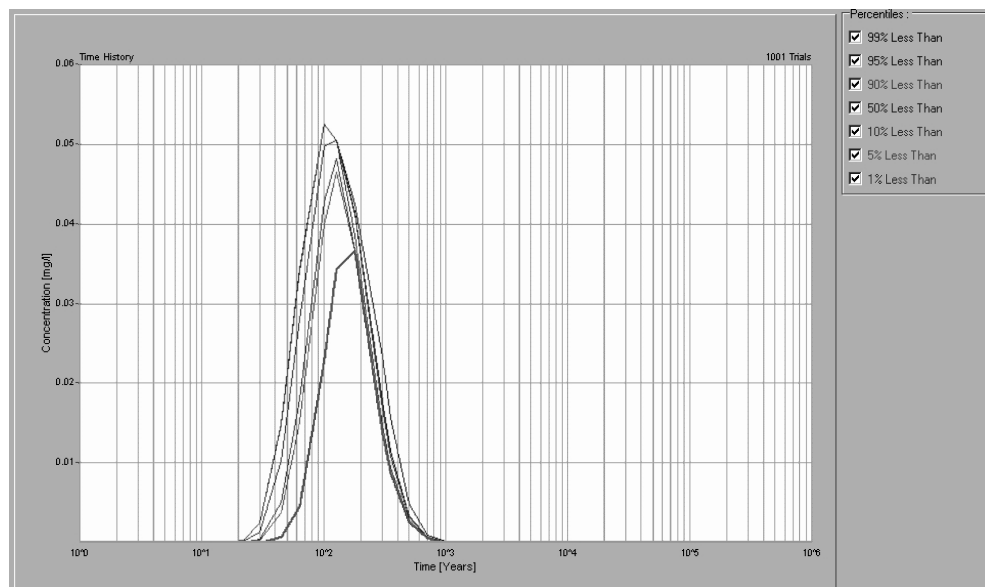Predicted leakage from the landfill site
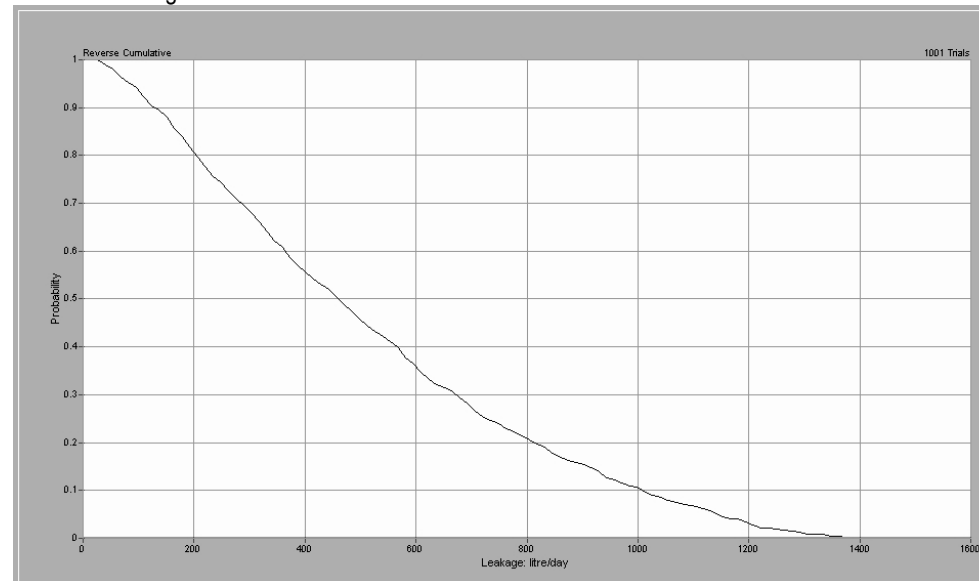
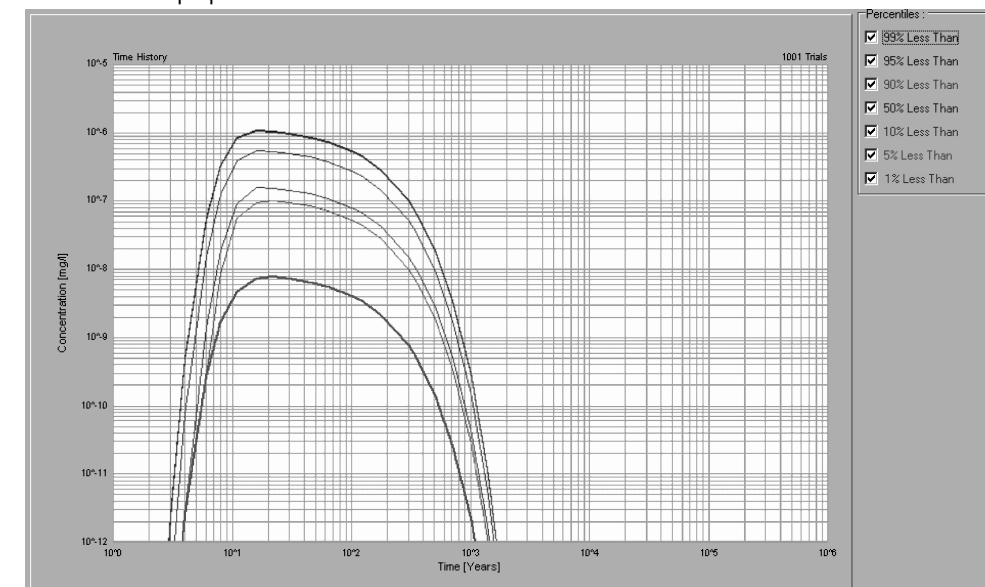Predicted toluene concentration in leachate

Predicted mecoprop concentration in leachate

Predicted toluene concentration at the base of the unsaturated zone

Predicted mecoprop concentration at the base of the unsaturated zone

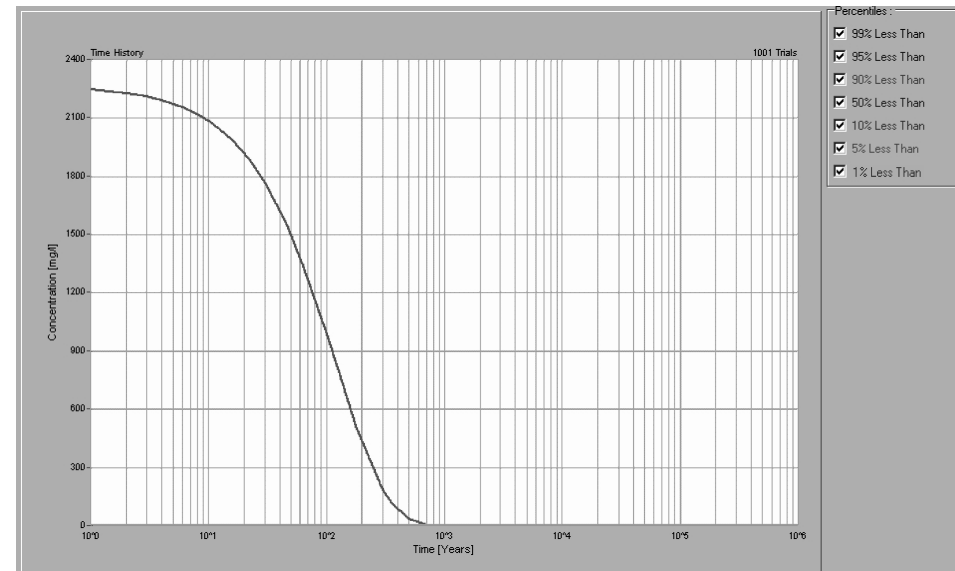| Date	25/03/03	Title **Predicted leakage from the landfill site, toluene and mecoprop concentrations using LandSim 2.02**	*Figure*
Project No.	02523429		**1**
Created by	C.W.		
File No.	5219973		

Predicted chloride concentration in leachate (LandSim 2.02 source concentration)
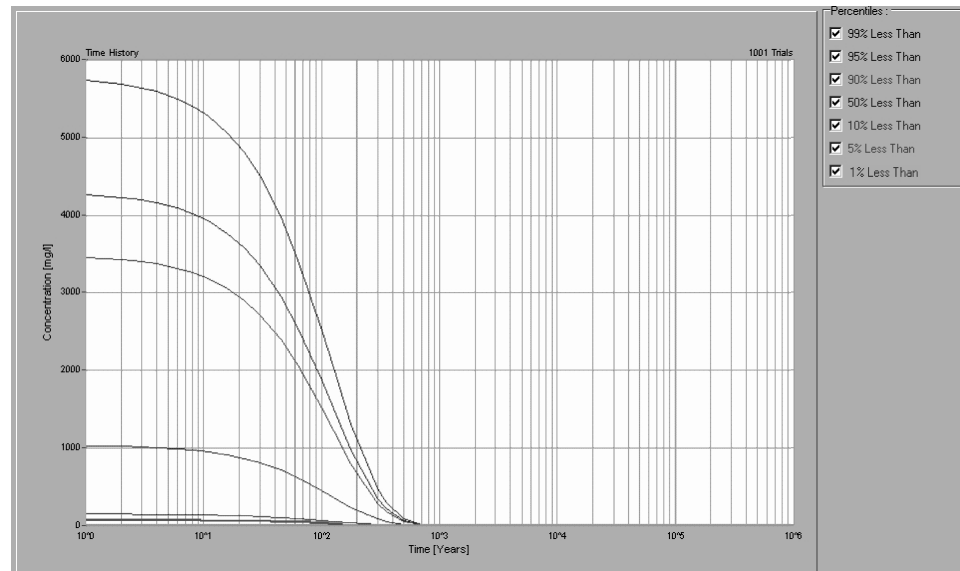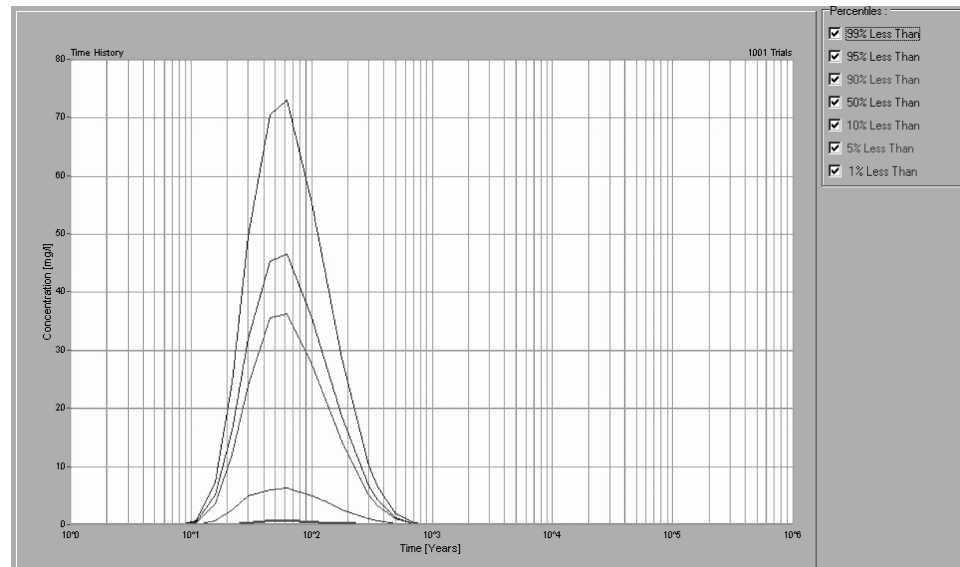
Predicted chloride concentration in leachate (Source concentration used in GoldSim model)

Predicted chloride concentration in leachate (Proposed source concentration for LandSim 2.5)
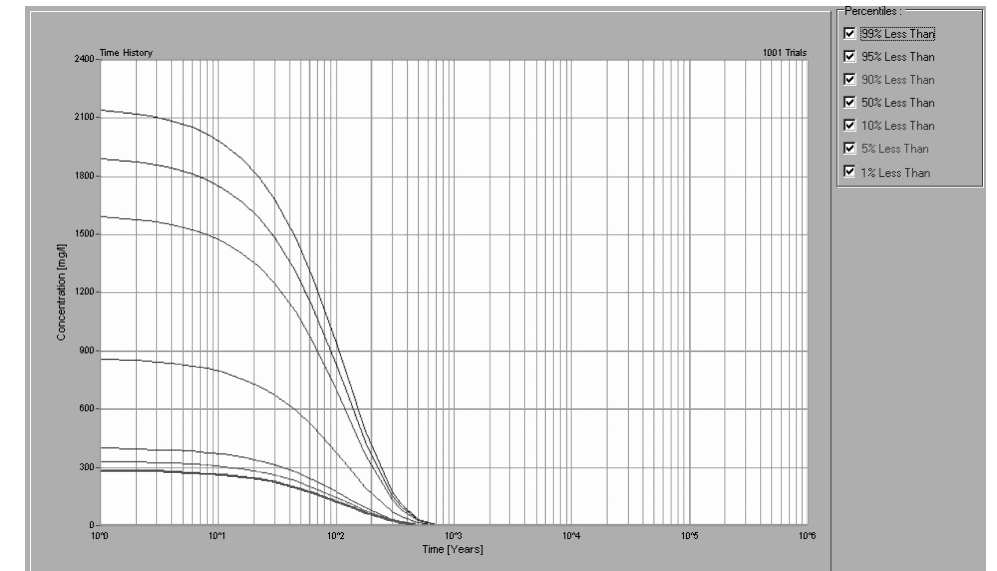
Predicted chloride concentration at the saturated zone receptor (LandSim 2.02 source concentration)

Predicted chloride concentration at the saturated zone receptor (Source concentration used in GoldSim model)

Predicted chloride concentration at the saturated zone receptor (Proposed source concentration for LandSim 2.5)
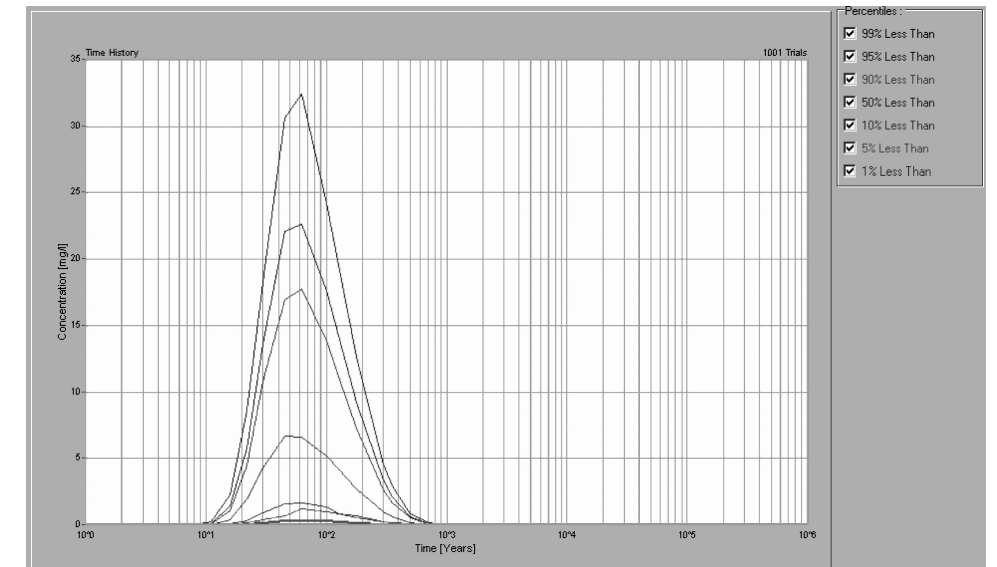
Date	25/03/03	Title *Predicted chloride concentrations using LandSim 2.02*	*Figure*
Project No.	02523429		
Created by	C.W.		**2**
File No.	5219974		

Predicted cadmium concentration in leachate (LandSim 2.02 source concentration)

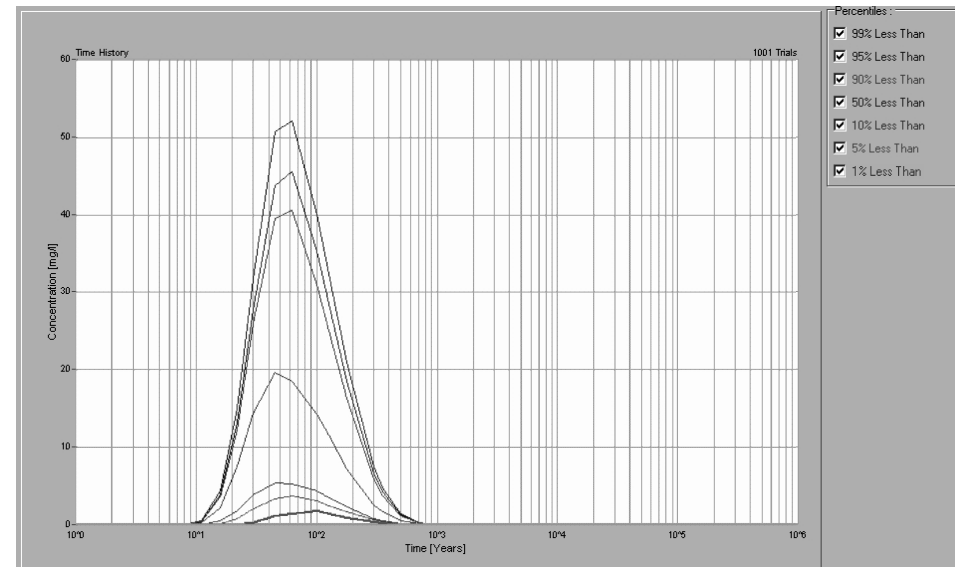Predicted cadmium concentration in leachate (Source concentration used in GoldSim model)
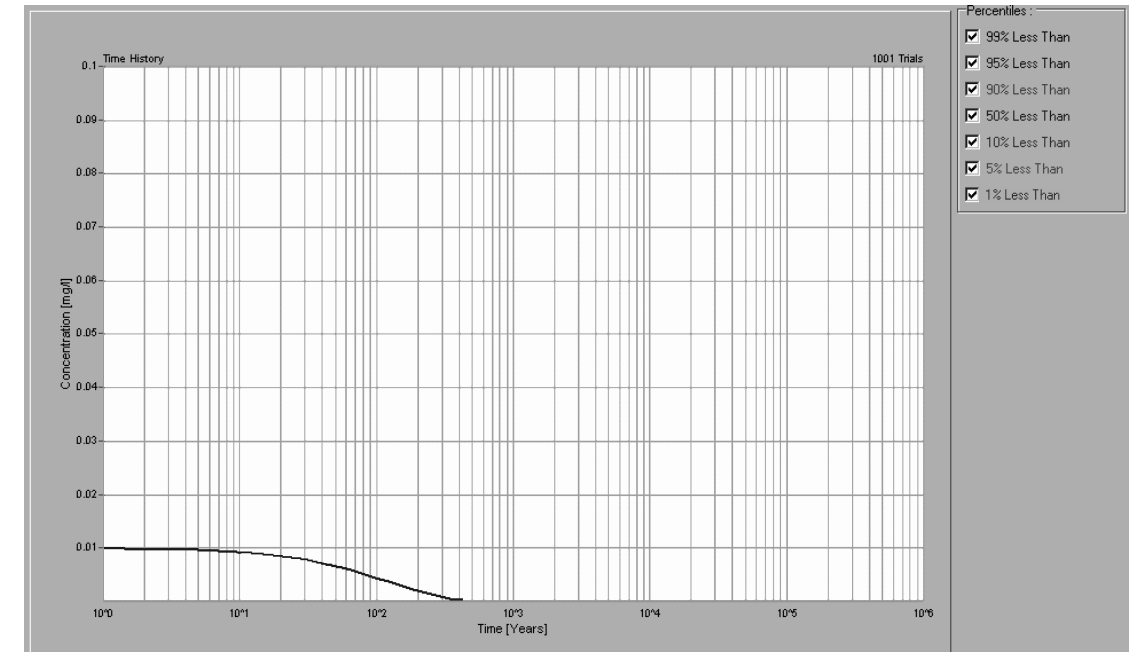
Predicted cadmium concentration at the base of the unsaturated zone (LandSim 2.02 source concentration)

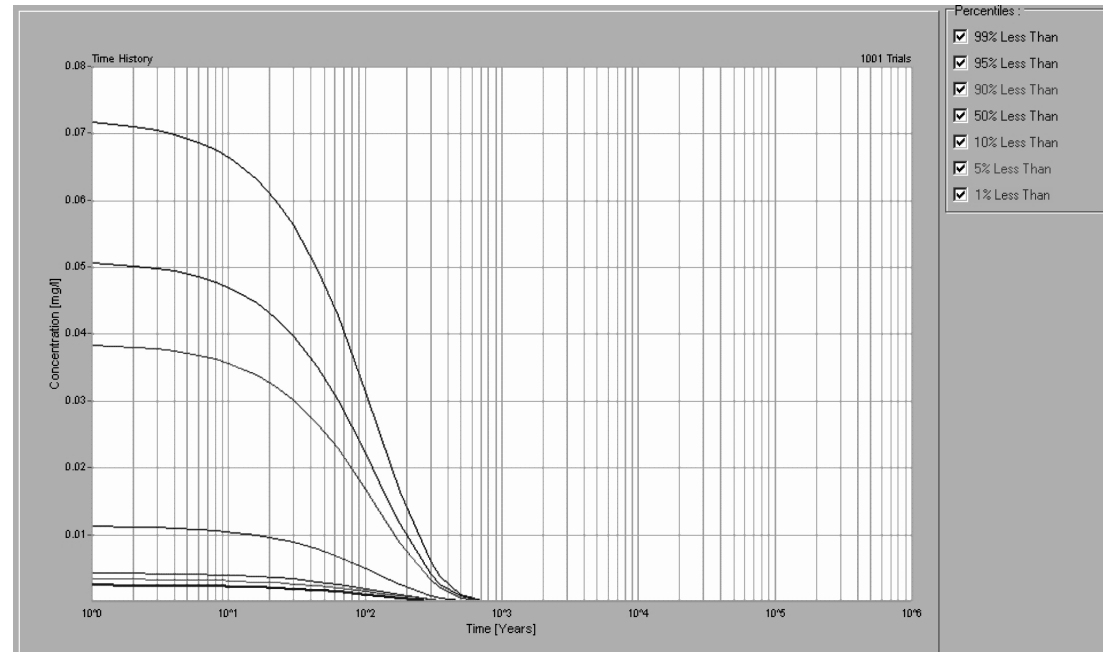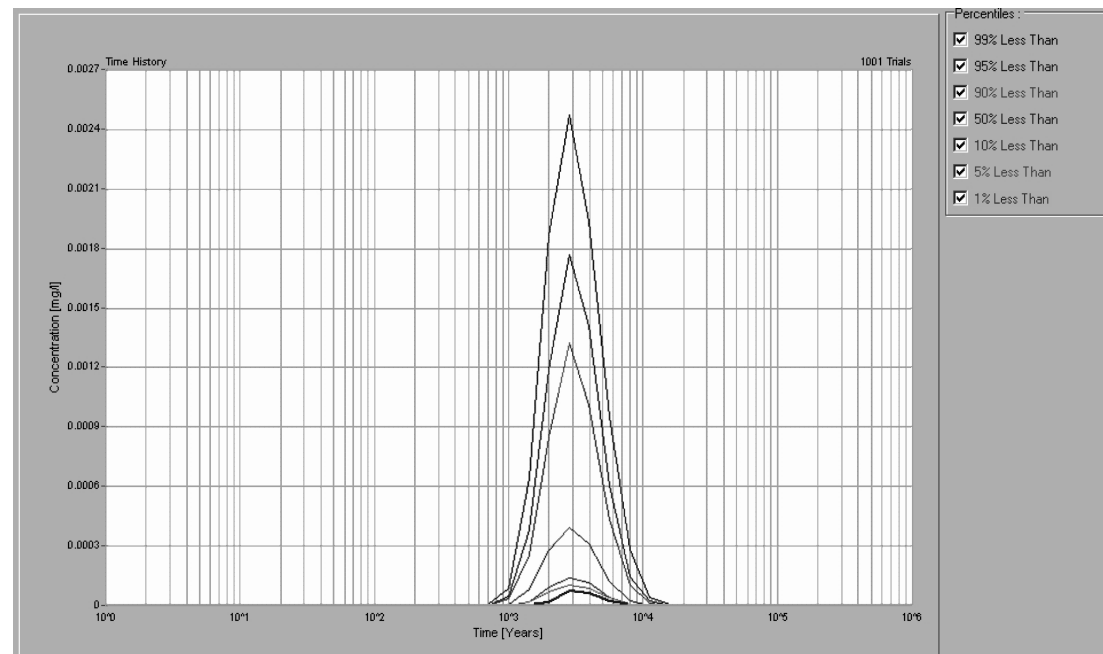Predicted cadmium concentration at the base of the unsaturated zone(Source concentration used in GoldSim model)

Date	25/03/03	Title	Figure
Project No.	02523429	*Predicted cadmium concentrations using LandSim 2.02.*	
Created by	C.W.		*3*
File No.	5219975		

Infiltration to landfill site

Predicted flow to off site disposal

Predicted head of leachate in waste

Predicted surface water breakout

Predicted leakage from the landfill

Legend

—— 40 years management control

—— 100 years management control

—— 400 years management control

Date	25/03/03	*Title*
Project No.	02523429	***Hydraulic predictions of the GoldSim (LandSim 2.5) model.***
Created by	C.W.	
File No.	5219976	

Figure

4

Predicted chloride concentration in leacahte

Predicted cadmium concentration in leacahte

Predicted toluene concentration in leacahte

Predicted mecoprop concentration in leacahte

Predicted cadmium concentration at the base of the unsaturated zone

Predicted toluene concentration at the base of the unsaturated zone

Predicted mecoprop concentration at the base of the unsaturated zone

Predicted chloride concentration at the saturated zone receptor

<u>*Legend*</u>

40 years management control

100 years management control

400 years management control

Date	25/03/03
Project No.	02523429
Created by	C.W.
File No.	5219977

Title
Concentrations predicted by the GoldSim (LandSim 2.5) model.

Figure

5

Appendix 1

Landsim 2.02 model summary - using Landsim 2.02 leachate concentrations

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Calculation Settings

Number of iterations: 1001
Calculated values used as input
Unsaturated Pathway:
    Retarded values used for simulation
    Biodegradation
Saturated Vertical Pathway:
    No Vertical Pathway
Aquifer Pathway:
    Retarded values used for simulation
    Biodegradation
Timeslices at: 30, 100, 300, 1000 (years)

Contaminant Half-lives:

Unsaturated Pathway
    Cadmium   SINGLE(1E+09)
    Chloride   SINGLE(1E+09)
    Toluene   SINGLE(1E+09)
    Mecoprop   SINGLE(1)

Aquifer Pathway
    Cadmium   SINGLE(1E+09)
    Chloride   SINGLE(1E+09)
    Toluene   SINGLE(1E+09)
    Mecoprop   SINGLE(1)

RECORD OF RISK ASSESSMENT MODEL

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Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3a version 2.sim
File Date: 01 04 03, 12:36 PM

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Infiltration Information

Water entering landfill through top (mm/year):
      SINGLE(50)

Justification for Specified Infiltration
Unjustified

Barrier Information

Justification for Engineered Barrier Type
Unjustified

There is a composite barrier
Liner installed under CQA
Design thickness of liner:
SINGLE(1) (m)

Justification for Comp: Clay or BES Substrate Properties
Presently unjustified change made to user specified value

Hydraulic conductivity of mineral lower liner (m/s):
      SINGLE(1E-09)
Membrane defects (per hectare):
      Pin holes: TRIANG(0.0, 25.0, 25.0)
      Holes: TRIANG(0.0, 5.0, 5.0)
      Tears: TRIANG(0.0, 0.1, 2.0)

Justification for Comp: Flexible Membrane Liner
Unjustified value

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3a version 2.sim
File Date: 01 04 03, 12:36 PM

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Drainage Information

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

Justification for Specified Head
 Unjustified

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3a version 2.sim
File Date: 01 04 03, 12:36 PM

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Unsaturated zone pathway parameters

Modelled as unsaturated pathway
Pathway length (m):
    SINGLE(5)
    Flow Model: porous medium
Pathway moisture content (fraction):
    SINGLE(0.3)

Justification for Unsat Zone Geometry
Presently unjustified change made to user specified
value

Pathway hydraulic conductivity values (m/s):
    SINGLE(0.00001)

Justification for Unsat Zone Hydraulics Properties
Unjustified

Pathway longitudinal dispersivity (m):
    SINGLE(0.5)

Justification for Unsat Zone Dispersion Properties
Values based on Pathway Geometry

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Retardation parameters for Unsaturated zone pathway

Modelled as unsaturated pathway.

Uncertainty in Kd (l/kg):

Cadmium: SINGLE(20)
Chloride: SINGLE(0)
Toluene: SINGLE(0.29)
Mecoprop: SINGLE(0.02)

Justification for Kd Values by Species
Presently unjustified change made to user specified
value

Pathway Density (kg/l):
SINGLE(2)

Aquifer Pathway Dimensions

Pathway length (m):
UNIFORM(100.0, 300.0)
Pathway width (m):
SINGLE(200)

Cell dimensions

Cell width:	200 (m)
Cell length:	200 (m)
Cell top area (ha):	6
Cell base area (ha):	4
Number of cells:	1
Total Base Area (ha):	4
Total Top Area (ha):	6

Justification for Landfill Geometry
Unjustified

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3a version 2.sim
File Date: 01 04 03, 12:36 PM

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Source concentrations of contaminants

All units in milligrams per litre
Uncertainty as logarithmic triangular distribution
Declining source term

Final waste thickness (m):
SINGLE(20)
Field Capacity (fraction):
SINGLE(0.3)

	Minimum	Likely	Maximum
Cadmium	1.9E-3	1.01E-2	1.05E-1
Chloride	3.66E1	2.27E3	7.76E3
Toluene	8.7E-2	8.7E-2	8.7E-2
Mecoprop	2.18E-2	2.18E-2	2.18E-2

Justification for Species Concentration in Leachate
Presently unjustified change made to user specified
value

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Vertical pathway parameters

No Vertical Pathway

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3a version 2.sim
File Date: 01 04 03, 12:36 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3a version 2.sim
File Date: 01 04 03, 12:36 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Saturated zone pathway parameters

Modelled as aquifer pathway.

Mixing zone (m):
SINGLE(5)
Pathway porosity (fraction):
SINGLE(0.3)

Justification for Aquifer Geometry
Unjustified

Pathway regional gradient:
SINGLE(0.01)
Pathway hydraulic conductivity values (m/s):
SINGLE(4.7532E-05)

Justification for Aquifer Hydraulics Properties
Unjustified

Pathway longitudinal dispersivity (m):
UNIFORM(10.0, 30.0)
Pathway transverse dispersivity (m):
UNIFORM(3.0, 9.0)

Justification for Aquifer Dispersion Details
Values based on Pathway Geometry

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Retardation parameters for Saturated zone pathway

Modelled as aquifer pathway.

Uncertainty in Kd (l/kg):

Cadmium: SINGLE(20)
Chloride: SINGLE(0)
Toluene: SINGLE(0.29)
Mecoprop: SINGLE(0.02)

Justification for Kd Values by Species
Presently unjustified change made to user specified
value

Pathway Density (kg/l):
SINGLE(2)

Appendix 2

LandSim 2.02 model summary - using proposed LandSim 2.5 leachate concentrations

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5   Page 1 of 9
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Calculation Settings

Number of iterations: 1001
Calculated values used as input
Unsaturated Pathway:
   Retarded values used for simulation
   Biodegradation
Saturated Vertical Pathway:
   No Vertical Pathway
Aquifer Pathway:
   Retarded values used for simulation
   Biodegradation
Timeslices at: 30, 100, 300, 1000 (years)

Contaminant Half-lives:

   Unsaturated Pathway
      Cadmium   SINGLE(1E+09)
      Chloride   SINGLE(1E+09)
      Toluene   SINGLE(1E+09)
      Mecoprop   SINGLE(1)

   Aquifer Pathway
      Cadmium   SINGLE(1E+09)
      Chloride   SINGLE(1E+09)
      Toluene   SINGLE(1E+09)
      Mecoprop   SINGLE(1)

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Infiltration Information

Water entering landfill through top (mm/year):
SINGLE(50)

Justification for Specified Infiltration
Unjustified

Barrier Information

Justification for Engineered Barrier Type
Unjustified

There is a composite barrier
Liner installed under CQA
Design thickness of liner:
SINGLE(1) (m)

Justification for Comp: Clay or BES Substrate Properties
Presently unjustified change made to user specified value

Hydraulic conductivity of mineral lower liner (m/s):
SINGLE(1E-09)
Membrane defects (per hectare):
Pin holes: TRIANG(0.0, 25.0, 25.0)
Holes: TRIANG(0.0, 5.0, 5.0)
Tears: TRIANG(0.0, 0.1, 2.0)

Justification for Comp: Flexible Membrane Liner
Unjustified value

RECORD OF RISK ASSESSMENT MODEL

Page 3 of 9

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Drainage Information

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

Justification for Specified Head
Unjustified

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Unsaturated zone pathway parameters

Modelled as unsaturated pathway
Pathway length (m):
    SINGLE(5)
    Flow Model: porous medium
Pathway moisture content (fraction):
    SINGLE(0.3)

Justification for Unsat Zone Geometry
Presently unjustified change made to user specified value

Pathway hydraulic conductivity values (m/s):
    SINGLE(0.00001)

Justification for Unsat Zone Hydraulics Properties
Unjustified

Pathway longitudinal dispersivity (m):
    SINGLE(0.5)

Justification for Unsat Zone Dispersion Properties
Values based on Pathway Geometry

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Retardation parameters for Unsaturated zone pathway

Modelled as unsaturated pathway.

Uncertainty in Kd (l/kg):

Cadmium: SINGLE(20)
Chloride: SINGLE(0)
Toluene: SINGLE(0.29)
Mecoprop: SINGLE(0.02)

Justification for Kd Values by Species
Presently unjustified change made to user specified value

Pathway Density (kg/l):
SINGLE(2)

Aquifer Pathway Dimensions

Pathway length (m):
UNIFORM(100.0, 300.0)
Pathway width (m):
SINGLE(200)

Cell dimensions

Cell width:	200 (m)
Cell length:	200 (m)
Cell top area (ha):	6
Cell base area (ha):	4
Number of cells:	1
Total Base Area (ha):	4
Total Top Area (ha):	6

Justification for Landfill Geometry
Unjustified

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5

Project Number: Risk 0000

File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim

File Date: 01 04 03, 12:40 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Source concentrations of contaminants

All units in milligrams per litre
Uncertainty as logarithmic triangular distribution
Declining source term

Final waste thickness (m):
SINGLE(20)
Field Capacity (fraction):
SINGLE(0.3)

	Minimum	Likely	Maximum
Cadmium	1.01E-2	1.01E-2	1.01E-2
Chloride	2.27E3	2.27E3	2.27E3
Toluene	8.7E-2	8.7E-2	8.7E-2
Mecoprop	2.18E-2	2.18E-2	2.18E-2

Justification for Species Concentration in Leachate
Presently unjustified change made to user specified
value

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Vertical pathway parameters

No Vertical Pathway

Model used to compare the results of LandSim 2.02 with LandSim 2.5

No Vertical Pathway

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Saturated zone pathway parameters

Modelled as aquifer pathway.

Mixing zone (m):
    SINGLE(5)
Pathway porosity (fraction):
    SINGLE(0.3)

Justification for Aquifer Geometry
Unjustified

Pathway regional gradient:
    SINGLE(0.01)
Pathway hydraulic conductivity values (m/s):
    SINGLE(4.7532E-05)

Justification for Aquifer Hydraulics Properties
Unjustified

Pathway longitudinal dispersivity (m):
    UNIFORM(10.0, 30.0)
Pathway transverse dispersivity (m):
    UNIFORM(3.0, 9.0)

Justification for Aquifer Dispersion Details
Values based on Pathway Geometry

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3b version 2.sim
File Date: 01 04 03, 12:40 PM

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Retardation parameters for Saturated zone pathway

Modelled as aquifer pathway.

Uncertainty in Kd (l/kg):

Cadmium: SINGLE(20)
Chloride: SINGLE(0)
Toluene: SINGLE(0.29)
Mecoprop: SINGLE(0.02)

Justification for Kd Values by Species
Presently unjustified change made to user specified value

Pathway Density (kg/l):
SINGLE(2)

Appendix 3

LandSim 2.02 model summary - using the single value for leachate contaminant concentration used by the LandSim 2.5 model

RECORD OF RISK ASSESSMENT MODEL

Project: LandSim 2.5
Project Number: Risk 0000
File Title: P:\2002\3_wm\02523429 - LandSim 2.5\450-WIP\comparative exercise\23_3c version 2.sim
File Date: 01 04 03, 12:42 PM

Page 1 of 9

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Calculation Settings

Number of iterations: 1001
Calculated values used as input
Unsaturated Pathway:
   Retarded values used for simulation
   Biodegradation
Saturated Vertical Pathway:
   No Vertical Pathway
Aquifer Pathway:
   Retarded values used for simulation
   Biodegradation
Timeslices at: 30, 100, 300, 1000 (years)

Contaminant Half-lives:

   Unsaturated Pathway
      Chloride   SINGLE(1E+09)
      Toluene   SINGLE(1E+09)
      Mecoprop   SINGLE(1)

   Aquifer Pathway
      Chloride   SINGLE(1E+09)
      Toluene   SINGLE(1E+09)
      Mecoprop   SINGLE(1)

RECORD OF RISK ASSESSMENT MODEL

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Infiltration Information

Water entering landfill through top (mm/year):
    SINGLE(50)

Justification for Specified Infiltration
Unjustified

Barrier Information

Justification for Engineered Barrier Type
Unjustified

There is a composite barrier
Liner installed under CQA
Design thickness of liner:
SINGLE(1) (m)

Justification for Comp: Clay or BES Substrate Properties
Presently unjustified change made to user specified value

Hydraulic conductivity of mineral lower liner (m/s):
    SINGLE(1E-09)
Membrane defects (per hectare):
    Pin holes: TRIANG(0.0, 25.0, 25.0)
    Holes: TRIANG(0.0, 5.0, 5.0)
    Tears: TRIANG(0.0, 0.1, 2.0)

Justification for Comp: Flexible Membrane Liner
Unjustified value

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Drainage Information

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

Justification for Specified Head
Unjustified

Model used to compare the results of LandSim 2.02 with LandSim 2.5

RECORD OF RISK ASSESSMENT MODEL

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Unsaturated zone pathway parameters

Modelled as unsaturated pathway
Pathway length (m):
    SINGLE(5)
    Flow Model: porous medium
Pathway moisture content (fraction):
    SINGLE(0.3)

Justification for Unsat Zone Geometry
    Presently unjustified change made to user specified
    value

Pathway hydraulic conductivity values (m/s):
    SINGLE(0.00001)

Justification for Unsat Zone Hydraulics Properties
    Unjustified

Pathway longitudinal dispersivity (m):
    SINGLE(0.5)

Justification for Unsat Zone Dispersion Properties
    Values based on Pathway Geometry

RECORD OF RISK ASSESSMENT MODEL

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Retardation parameters for Unsaturated zone pathway

Modelled as unsaturated pathway.

Uncertainty in Kd (l/kg):

Chloride: SINGLE(0)
Toluene: SINGLE(0.29)
Mecoprop: SINGLE(0.02)

Justification for Kd Values by Species
Presently unjustified change made to user specified
value

Pathway Density (kg/l):
SINGLE(2)

Aquifer Pathway Dimensions

Pathway length (m):
UNIFORM(100.0, 300.0)
Pathway width (m):
SINGLE(200)

Cell dimensions

Cell width:	200 (m)
Cell length:	200 (m)
Cell top area (ha):	6
Cell base area (ha):	4
Number of cells:	1
Total Base Area (ha):	4
Total Top Area (ha):	6

Justification for Landfill Geometry
Unjustified

RECORD OF RISK ASSESSMENT MODEL

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Phase: Phase 1

Source concentrations of contaminants

All units in milligrams per litre
Uncertainty as logarithmic triangular distribution
Declining source term

Final waste thickness (m):
    SINGLE(20)
Field Capacity (fraction):
    SINGLE(0.3)

	Minimum	Likely	Maximum
Chloride	2.27E2	9.97E2	2.65E3
Toluene	8.7E-2	8.7E-2	8.7E-2
Mecoprop	2.18E-2	2.18E-2	2.18E-2

Justification for Species Concentration in Leachate
Presently unjustified change made to user specified
value

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Vertical pathway parameters

No Vertical Pathway

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Model used to compare the results of LandSim 2.02 with LandSim 2.5

Saturated zone pathway parameters

Modelled as aquifer pathway.

Mixing zone (m):
    SINGLE(5)
Pathway porosity (fraction):
    SINGLE(0.3)

Justification for Aquifer Geometry
Unjustified

Pathway regional gradient:
    SINGLE(0.01)
Pathway hydraulic conductivity values (m/s):
    SINGLE(4.7532E-05)

Justification for Aquifer Hydraulics Properties
Unjustified

Pathway longitudinal dispersivity (m):
    UNIFORM(10.0, 30.0)
Pathway transverse dispersivity (m):
    UNIFORM(3.0, 9.0)

Justification for Aquifer Dispersion Details
Values based on Pathway Geometry

RECORD OF RISK ASSESSMENT MODEL

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Model used to compare the results of LandSim 2.02 with LandSim 2.5

Retardation parameters for Saturated zone pathway

Modelled as aquifer pathway.

Uncertainty in Kd (l/kg):

Chloride: SINGLE(0)
Toluene: SINGLE(0.29)
Mecoprop: SINGLE(0.02)

Justification for Kd Values by Species
Presently unjustified change made to user specified
value

Pathway Density (kg/l):
SINGLE(2)

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