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Project identification

1. Defra Project code: WR0304 (WRT279)
2. Project title: Towards sustainable landfill: Passive fail-safe design and engineering’
3. Contractor organisation(s): Golder Associates (UK) Ltd

   Napier University
4. Total Defra project costs (agreed fixed price): £ 71,000
5. Project: start date .... 18 July 2006

   end date .... 15 February 2008

6. It is Defra's intention to publish this form.
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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

This research project's objectives are to understand the key issues associated with landfill closure that influence the ability of landfill to be included within a sustainable waste management system. Uncertainty will always surround the precise state of a landfill on its journey towards full chemical, biological and hydrogeological stabilisation. While an understanding of the key parameters that govern its progress is important, it is highly desirable to add passive fail-safe systems to landfills so that failure of aftercare systems do not result in large scale environmental impact. This project has developed a means of understanding the hydraulics and consequential flushing of organic and inorganic contaminants from the waste mass, and the time required to achieve a discharge that meets current groundwater and surface water standards.

When a landfill is fully drained (i.e. the leachate level is below its compliance level and is being actively pumped) then rainfall enters the waste mass either as direct precipitation onto the waste or via cap leakage. This water then flows vertically downwards until it enters the drainage system from where it is removed. Once a landfill floods and overtops then not all of the water that enters the site flows to the base. Water entering the landfill will flow through a substantially thinner (waste) unsaturated zone to enter saturated waste. A slow component of downwards flow will exist in response to basal leakage while a second component of flow will drive water laterally towards the side of the landfill where it will overtop the liner system. The Hydro-Bio-Mechanical (HBM) Model (McDougall, 2007) has been used extensively to investigate the hydraulics of various saturated landfill and land raise geometries.

The concept of fail-safe engineering relates to additions or modifications to standard landfill engineering to ensure that the inevitable failure of containment and leachate collection systems, and management control itself, will not result in groundwater and surface water pollution.

This study has explored the effects of different landfill site geometries and waste streams on the combined hydraulic and contaminant behaviour. Waste streams have differing properties including density, porosity, hydraulic conductivity, as well as different leaching characteristic. The latter includes the initial leachate concentration and key contaminants, as well as the rate of leaching that might occur.

Significant progress has been made in understanding the hydraulics of landfills as they enter their unmanaged post-closure period where certain landfill and land raise geometries make overflow almost inevitable. The results from the hydraulic modelling have allowed a more robust conceptual model of the leachate source term to be constructed that reacts to the differing flow zones that evolve within the waste. Based on this new and unique approach, it has been possible to simulate the contaminant release from waste sites as they enter and pass through this phase of their lifecycle, and to differentiate between the contaminant mass entering groundwater and that entering the surface water system.

The contaminant release and flushing of contaminants to groundwater and surface water has used an adaption of the GoldSim model originally developed for the Equilibrium study, but with some significant enhancements and the addition of a larger number of contaminants.

The report includes a summary of the key characteristic that influence the time take to stabilise waste residues likely to exist in the future once the influence of the Landfill Directive's biodegradable waste diversion targets have been met, and includes residues from MBT processes as well as incinerator bottom ash. Detailed results tables are included to highlight those contaminants that remain problematic in different waste site geometries, different waste types and if the different pathways.

The results have all been benchmarked against raw MSW disposed of to a Landfill Directive compliant landfill. Raw MSW routinely fails to meet the sustainability criteria defined in the report in relation to Mecoprop and ammoniacal nitrogen. Copper remains an issue for surface water discharges from landfills and land raises where the waste stream is incinerator bottom ash. Cadmium and ammoniacal nitrogen appear to be a constraint for MBT residue landfills and land raise sites.

As a general rule, shallow sites have less effect on groundwater quality but are more susceptible to overflow and hence will have a negative influence on surface water quality. Deep landfill sites have a greater propensity to have a negative influence on groundwater while having a lower probability of affecting surface water. Indeed one of the fail-safe options examined looked at intentionally increasing the permeability of side wall liners such that during normal (regulated) operations leakage of leachate would be unaffected. However, once leachate levels begin to increase there is an increased rate of leakage such that overflow is avoided. In doing so, a greater volume of soil is utilised in the attenuation of leachates and hence a greater reliance on the purifying powers of the unsaturated zone.

Recommendations for further study are also included.

SUMMARY REPORT

1 Introduction

1.1 Objectives

The overall aim of this research was:

- To investigate the engineering and design features for landfills that will ensure that during post-closure, the period of active management is minimised and control systems will fail-safe to make any emissions of gas or leachate acceptable.

Specific objectives within the overall aim are:

1. To model leachate accumulation in a fully contained completed landfill and predict its likely composition at key times;
2. To identify design options for the control of gas and leachate in post-closure landfills;
3. To consult all stakeholders on the practicality of conventional and innovative design options; and
4. To provide a specification for the acceptable wastes or treated wastes to be deposited in particular types of future landfills in order to improve sustainability.

In relation to these specific objectives this report has met these objectives with varying levels of success. Specifically, and using the same numbering system as above:

1. Modelling work undertaken has identified the evolution of leachate composition in different zones of the landfill and how these change with time. Specifically, one of the prime findings of this research is the identification of different flow zones within the landfill and the differing evolution of leachate strength within these zones.

2. Fail-safe engineering options have been identified and modelled to determine their likely success in mitigating environmental damage from waste disposal sites in the long term. While fail-safe engineering options assist in protecting the environment, no single option met all the criteria and none achieved full environmental protection in the event of a landfill being fully abandoned. Ultimately, as the research progressed most of the emphasis was placed on leachate and groundwater/surface water interaction, while landfill gas issues were largely dropped from the scope.

3. A stakeholder meeting was held and an interesting and useful exchange of views was accomplished that refocused the efforts of the research team in the latter part of the project with less emphasis being placed on desirable waste properties (designer waste as it was termed within the workshop) and more emphasis on the scenario modelling to understand the external controls on sustainable landfill.

4. As noted in (3) above, following the stakeholder workshop, the project team was directed to spend less time on this aspect of the study. While not included in this summary, the full report does, nevertheless, include a section on desirable waste properties.

Research undertaken as part of this contract has highlighted the role that site geometry has in evolution of a waste disposal site on its journey towards Equilibrium Status. Both landfill and land-raise sites have been examined along with a variety of waste streams, engineering options and management options.

It is worth setting out at the beginning of this summary that no fail-safe measures were determined that fully rendered disposal of MSW waste streams to landfill or land-raise a sustainable means of disposing of wastes and additional measures have been identified that would need to be put in place to achieve the overall objects (but these additional measures are not fail-safe engineering options – rather they are operational measures that would need to be undertaken at the time the sites are under the control of a waste management company).

In relation to the specific objectives, much of the effort expended in this contract is directed to modelling the evolution of leachate concentrations in post-closure landfills, and modelling the migration and impact assessment that results from a gradually failing liner and capping system with a site that is progressively filling with leachate.

This project is focussed upon understanding the key issues associated with landfill closure that influence the ability of landfill to be included within a sustainable waste management system and the ability to influence these factors by design. While an understanding of the key factors that govern its progress is important, it is highly desirable (and forms part of this research contract) to add passive fail-safe systems to landfills so that failure of aftercare systems does not result in unacceptable environmental impact.

This project is, in part, an extension of work already completed during the Equilibrium Study (Hall *et al*, 2007b). This current research has taken one of the issues raised in the Equilibrium Study (that relating to the need to allow a landfill site to achieve hydraulic equilibrium, prior to it achieving chemical or environmental equilibrium) and included this factor within the modelling. It is worth dwelling on this issue briefly as it is a key issue within this research project and one that we believe has been virtually ignored to date within the waste research community.

A landfill that enters completion will have the controls associated with gas and leachate management removed (or at least deactivated). A consequence of this will be an increase in leachate levels, albeit that we would hope that the leachate quality is relatively benign at this stage. That said, it is inevitable that there will be pockets of waste that have not been significantly flushed (Heimovaara *et al*, 2007) that will now be able to affect leachate quality. It is possible that a deterioration of residual leachate quality might occur. In its own right this might not be an issue; at some prior point in the site's life the leachate strength will have been higher and hence it could be assumed that no damage to the environment will occur if comparable contaminant levels are experienced again. However, while this might appear a not unreasonable observation, liner systems are likely to deteriorate with time, as are leachate collection systems. A small deterioration in leachate quality coupled with what might be a dramatic increase in leachate levels (once pumping is stopped) will lead to increased leakage that in turn could lead to an undesirable situation. Leakage to groundwater might be increased to a point that water quality standards are breached, and surface discharge of leachate could become a consequence of high leachate levels within the site. This surface discharge, occurring after the infrastructure has been removed, and possibly after institutional controls have ceased could result in the additional risks relating to contamination of surface water courses.

This research set out with an aim to answer a number of critical questions that arise from such a scenario, as well as providing a general overview in relation to measures that can be taken to reduce the long-term post closure period. The issues are:

- How long does it take for a landfill to become saturated?
- How do different geometries of landfill affect their ability to reach equilibrium?

- Is there likely to be a different leachate quality in the flux to groundwater compared to that likely to discharge to surface water? and
- What changes to landfill design could assist in mitigating the long-term effects of unmanaged landfills that have entered an unplanned or planned closure period?

The research has also updated the findings of the Equilibrium Study in that certain organic contaminants found in MSW have been added to the list of inorganic contaminants already examined. Furthermore, the conservative scenario (with equally conservative parameters) adopted for the Equilibrium Study has been updated to a more typical UK landfill. The original scenarios were based on a single geometry developed for modelling that underpinned the setting of Waste Acceptance Criteria. As such the scenario was developed to suit a typical "European" landfill. While the engineering requirements are standardised across Europe with the implementation of the Landfill Directive, UK geology is different and more varied than that of some of our European neighbours.

An early finding of this study is that two or more distinct flow zones develop within the landfill once the site reaches hydraulic equilibrium and starts to overflow. The evolution of the flow zones will have implications on the rate at which different parts of the site are flushed.

Mid-way through the research project a Stakeholder Workshop was held with the joint aims of early dissemination of the results of the research to interested parties and to other researchers and to solicit feedback on the project, its overall aims and direction from the stakeholder group. A report of the Workshop recording the significant discussion points has been produced.

2 Background

2.1 Previous Studies

The Equilibrium Study (Hall *et al*, 2007b) examined the likely management times of landfills that accepted post Landfill Directive residues resulting from the pre-treatment of municipal solid waste (MSW). The primary waste residues considered were raw MSW (for benchmarking only), various MBT residues and various forms of raw and treated incinerator bottom ash (IBA). The assessment was based on examining the length of time it was necessary to manage leachate to avoid any future breaches of groundwater quality.

Without active intervention in the form of deliberate *in situ* flushing of the wastes within the landfill, none of these waste streams resulted in management times that approached our understanding of sustainable.

2.2 Background to this Study

Once the leachate removal system is deactivated, leachate will continue to accumulate within the site via infiltration, but there will be only limited movement (horizontally or vertically) within the saturated zone within the landfill. Above the level of saturation the predominant direction will still continue to be vertical. While the rate of infiltration exceeds the rate of leakage through the liner, there will be a gradual build-up of leachate within the site. In the short-term[1], there are only two possible outcomes – either the site reaches a point where the increased heads of leachate cause ever increasing leakage rates to the point

[1] If the site has an HDPE liner element, then in the longer term, leakage is likely to increase in response to a decreasing liner performance and a lower head of leachate will be needed to balance the input from infiltration. If this happens then the leachate level may well fall.

that leakage equals infiltration (at which point the leachate level stabilises and one form of hydraulic equilibrium is formed), or the site overtops and leachate is discharged to the surface. Understanding these flow regimes became a prerequisite to examining options for fail-safe engineering. In order address these issues, three basic scenarios have been examined (differing geometries) so that an indication of the size of the zones can be determined.

2.3 Modelling Methods

Two different modelling methods have been used in the project. The hydraulic modelling has been undertaken by Napier University using its Hydro-Bio-Mechanical (HBM) model.

The HBM model has been modified and used extensively within this research project. The modelling has drawn on research undertaken by McDougall et al, 2001, McDougall et al, 2004, as well as work by Drury *et al*, 2003 in the development of a method of modelling the performance of an HDPE liner while considering the effects of gradual (but predictable) loss of liner integrity. This allowed development of a detailed flow model of the internal flow regime within the landfill based on infiltration and representative leakage rates based on the leachate (hydraulic) pressure acting on the liner system.

The contaminant source term and migration of contaminants based on the flow model results from the HBM model were undertaken using the GoldSim package. The software used in the Equilibrium project and is an adaptation of LandSim implemented within the GoldSim modelling platform. This method of implementation allowed considerable flexibility over the modelling including the stochastic treatment of management time (something that LandSim does not permit).

The significant changes from the model used for the Equilibrium Study included for (but are not limited to) the following:

- Increase in the number of contaminants that are modelled;
- The discretisation of a landfill cell to model the upper and lower flow zones;
- The inclusion of a surface breakout pathway; and
- Inclusion of a cap run-off module.

Representation of the surface water pathway is relatively simplistic, with flows of leachate and cap run-off being added together in a mixing cell prior to reporting concentrations.

3 Results of Flow Modelling

3.1 Large (Deep) Landfill Geometry

The flow regime obtained from HBM modelling is shown in Figure 1. It is complex but appears plausible with flow vectors indicating a general confluence of surface infiltration towards the point of overtopping. In addition it is worth noting that:

1. Flow above the phreatic surface, i.e. in the unsaturated zone, is predominantly vertical, of small magnitude, and largely unaffected by proximity to the overtopping discharge point, and
2. The confluence is evident in a band of elements that are level with the overtopping discharge point and in which the magnitude of the horizontal flow component increases with proximity to the overtopping discharge point.

Thus, the simulation suggests the existence of three distinct zones, as indicated in Figure 1:

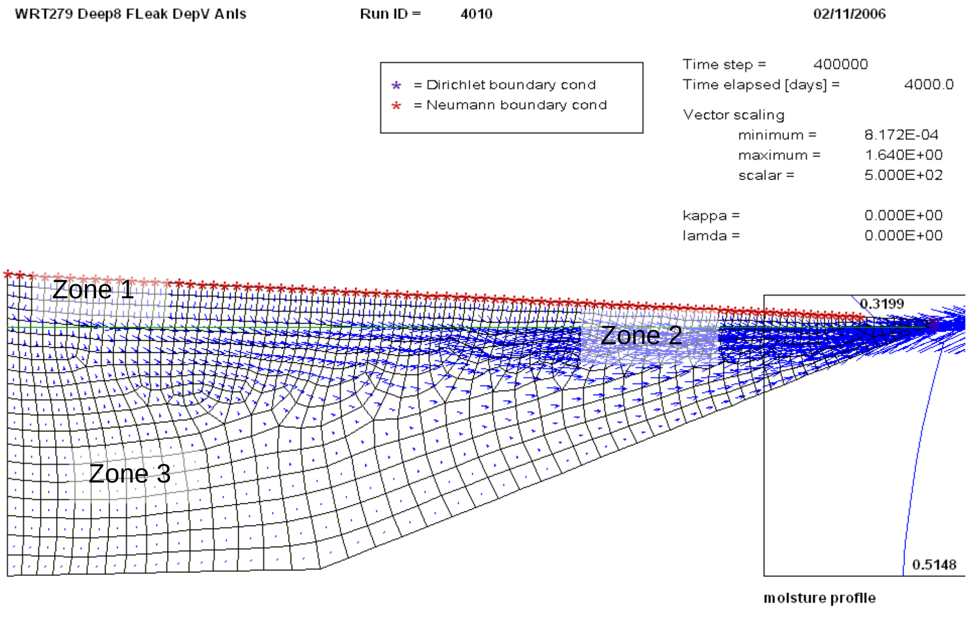
1. An upper unsaturated zone in receipt of relatively clean water, flowing vertically downwards, at a rate controlled by cap permeation;

2. An intermediate zone bounded above by the phreatic surface in which flow towards the overtopping discharge point is dominant. The accumulation of flow from the upper unsaturated zone means that the flow regime here is predominantly horizontal with relative magnitude strongly dependent on the proximity of overtopping discharge point. At points distant from the overtopping discharge point the intermediate zone is barely distinguishable. Anisotropy and cap infiltration control the absolute flow rates; and

3. A lower stagnant zone in which flow magnitudes are markedly less than in either the upper or the intermediate zones. Flow in the stagnant zone is controlled by liner leakage, which in turn is dependent on leachate head. Flow vectors are predominantly vertical at locations distal to the point of overtopping where, leachate heads are greatest. At locations closer to the overtopping discharge point and further up the sidewall liner, heads are less so liner leakage is smaller and flow tends towards the confluent pattern that is evident in the intermediate zone.

Figure 2, shows the same flow scenario as Figure 1 but with a seepage vector scalar contoured to give an indication of the spatial variation of flux within the system that spans over 3 orders of magnitude, with near stagnant conditions at the base of the site and considerably higher flows within the upper layers of the landfill.

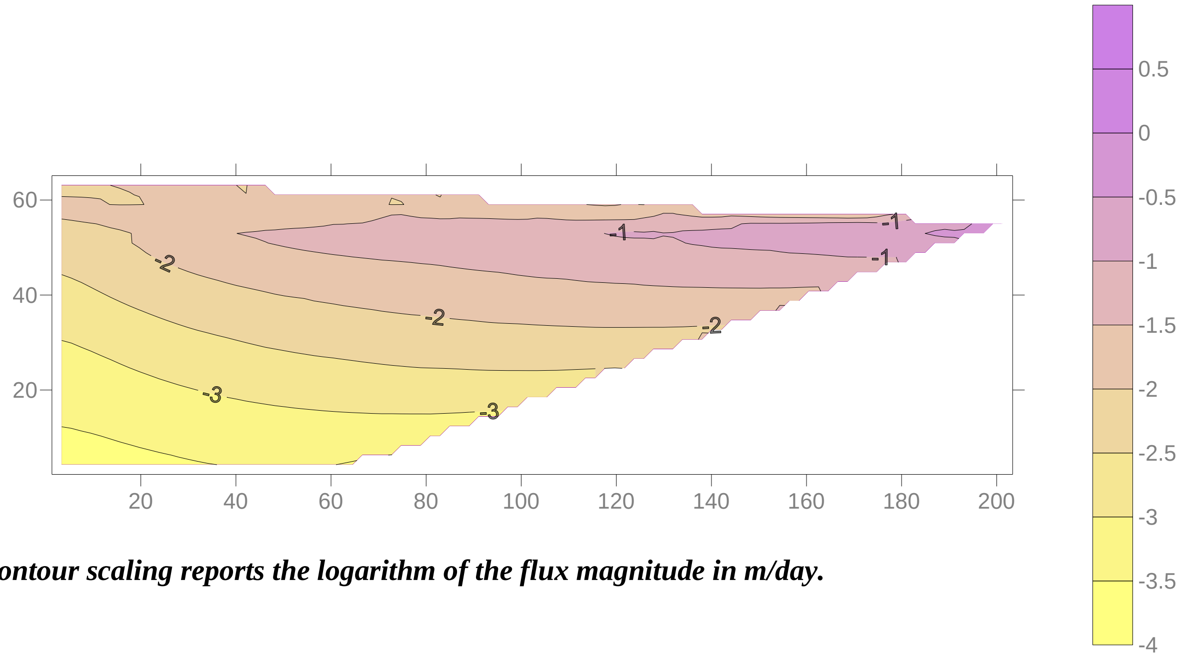
Figure 1: Simulation 8: Flow Regime, Moisture Profile and Main Flow Zones



Zone 1 is essentially the unsaturated part of the landfill that transmits infiltration that has entered via cap leakage. Zone 3 is virtually stagnant and transmits leachate through it at a rate comparable to the liner leakage rate. In this scenario, the liner is a composite Clay/HDPE liner with the mineral component of the liner having a hydraulic conductivity of 1.0E-10 m/s. The upper middle zone (Zone 2) transmits the leachate that is infiltrating, in excess of the leakage rate, horizontally to the overflow point.

The development of these zones is partly a function of the geometry of the landfill and partly the function of the variable properties of MSW and MBT residues with depth within the landfill (with lower hydraulic conductivities with increasing load). This deep scenario is able to overflow (with a high leachate head) for only a short period during the time dependent contaminant modelling as the liner degradation (which increases the effective permeability of the liner) eventually causes a fall in leachate levels to below the overflow point and Zone 2 ceases to exist.

Figure 2 Contours of the Vector Magnitude for the Overflowing Deep Site

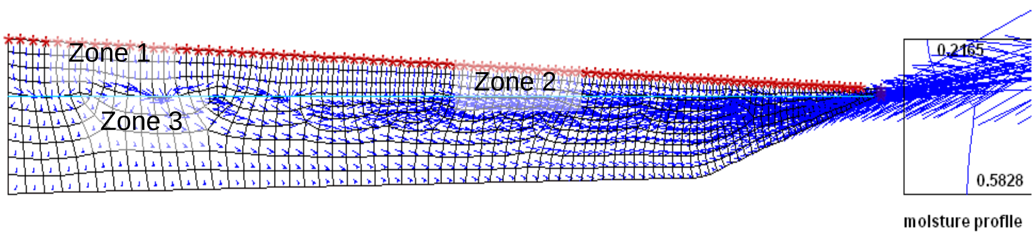


NB Contour scaling reports the logarithm of the flux magnitude in m/day.

3.2 Medium Depth Landfill

Figure 3 shows the flow regime that develops in the Medium Depth Landfill. A similar relationship develops in the medium site geometry with the same 3 zones developing in the waste mass. The only difference in this scenario is the geometry of the landfill (albeit that the volume of waste remains constant).

Figure 3 Medium Site Overflow Flow Regime



Because the overflow point is lower in this scenario relative to the base of the Site when compared to the deep site, the heads that develop in the landfill are much lower and hence the amount of leakage is lower. For this reason, the magnitude of the vectors in the lower portion of the Site (Zone 3) are lower than the deep site scenario. Furthermore, during the transient contaminant transport modelling undertaken with GoldSim, this Site continues to overflow throughout the time period modelled.

Figure 4 Contours of the Vector Magnitude for the Overflowing Medium Site

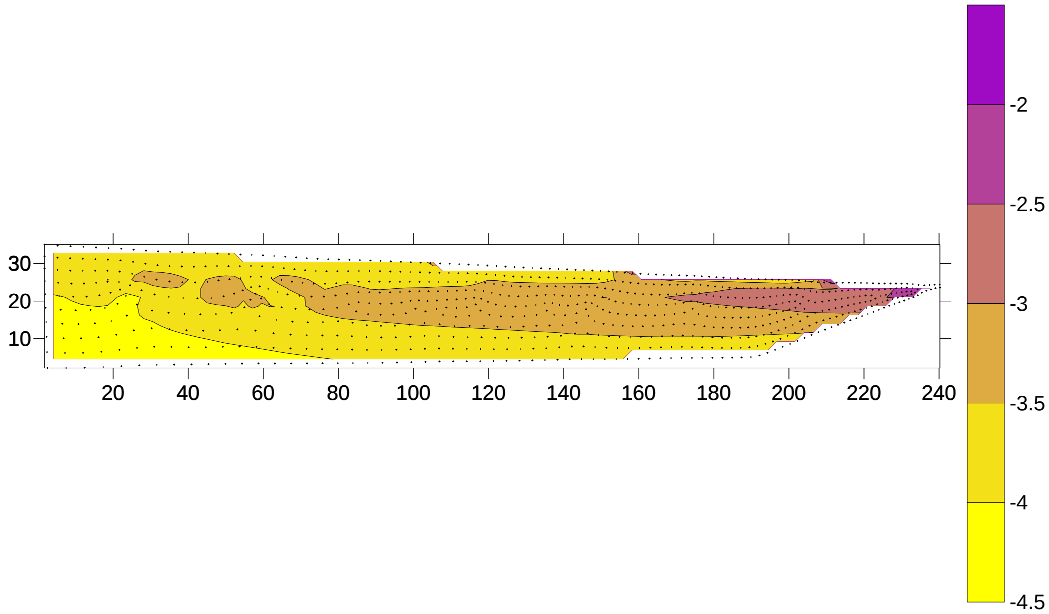
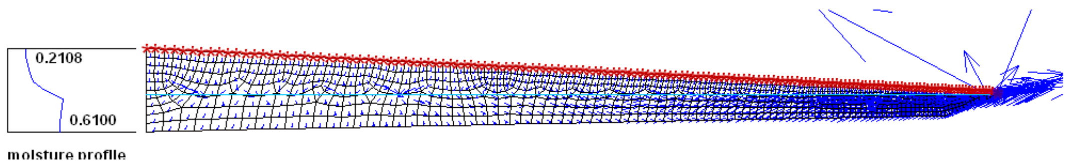


Figure 4 shows the same scenario as a contoured vector plot showing the order of magnitude of fluid flux within the landfill.

3.3 Shallow Site Landfill

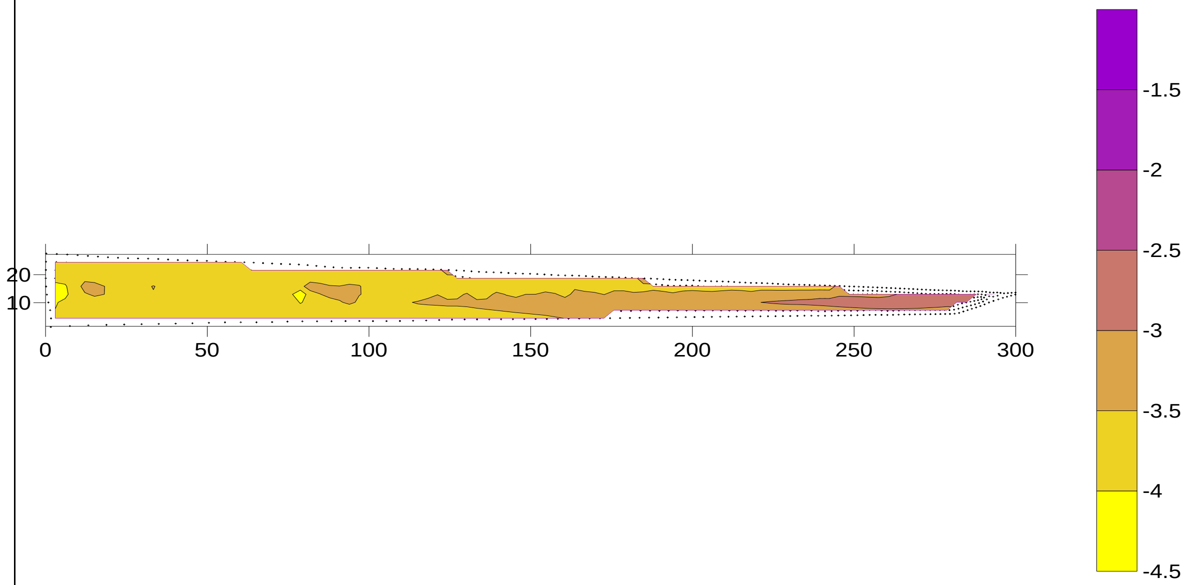
Within the shallow site, the definition of Zone 2 is less clear towards the centre of the Site although it is present nearer the perimeter of the Site. This is largely a result of the reduced waste thickness which in turn will result in more homogeneous hydraulic conductivity values. Furthermore, because the waste pile is relatively shallow, the hydraulic conductivity of the wastes varies only slightly and is more permeable at depth compared to either the medium or deep scenarios already examined.

Figure 5 Shallow Site Overflow Flow Regime



The flow regime (without the Zone notations) is shown in Figure 5. Zone 1 lies in the unsaturated zone above the water level (indicated by the light blue line) and Zone 3 lies below the water level in the centre of the site with the formation of Zone 2 conditions only near the site perimeter. Figure 6 shows the Contoured Vector Plot for the Shallow Site geometry.

Figure 6 Contours of the Vector Magnitude for the Overflowing Shallow Site

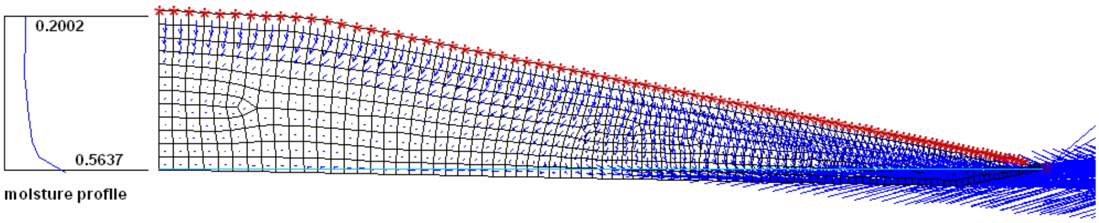


3.4 Land-Raise Geometry

The land-raise scenario presents a slightly different flow regime largely because the degree of saturation that can develop once leachate management ceases is relatively limited as the overflow point will be the Site's peripheral bund (often no more that around 5 m high). Such a regime presents a flow field not dissimilar to that assumed in the Equilibrium Project where infiltration was assumed to flush all parts of the waste site in equal measure.

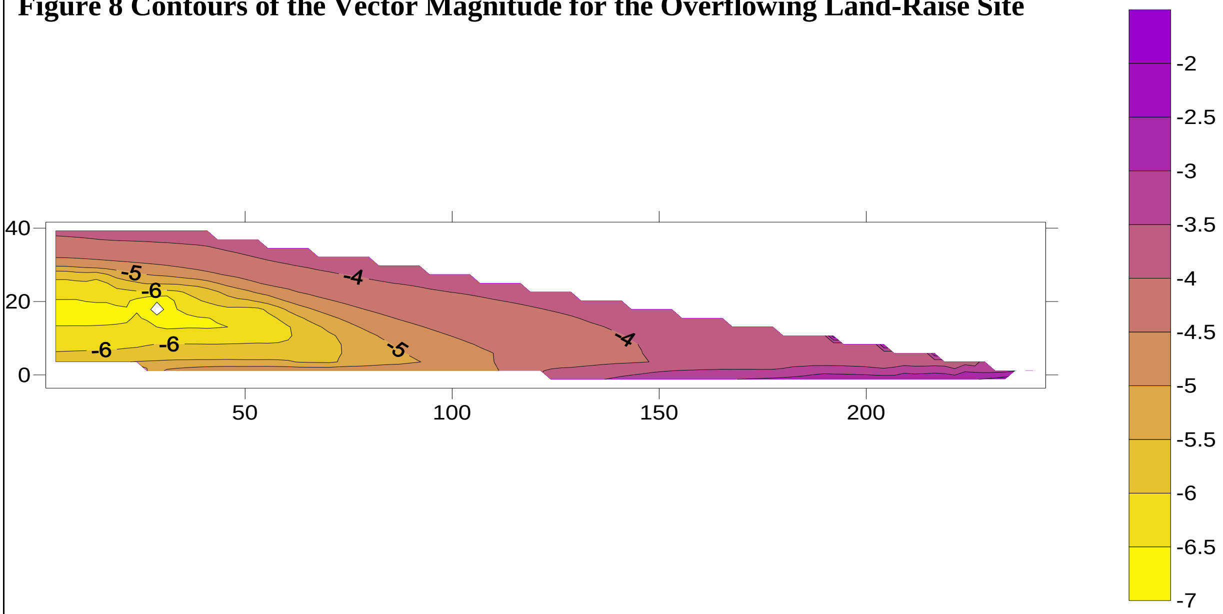
The flow regime is shown in Figure 7 and the contoured Vector Plot shown in Figure 8.

Figure 7 Land-Raise Site Overflow Flow Regime



Where distinct horizontal flow regimes are developed, it is predicted that the upper zone will be flushed more readily than the lower zone. This is enhanced by the fact that the upper zone in all but the IBA sites will have a higher hydraulic conductivity than the lower, near stagnant, zone. (We have assumed that for IBA sites the waste hydraulic conductivity does not vary with depth as it does for both raw MSW and for MBT residues.)

Figure 8 Contours of the Vector Magnitude for the Overflowing Land-Raise Site



During the research contract a methodology was developed for assessing the time to flood a landfill that did not require access to sophisticated modelling methods. The methodology developed is presented in Appendix 4 of the full report.

4 Contaminant migration impact assessment

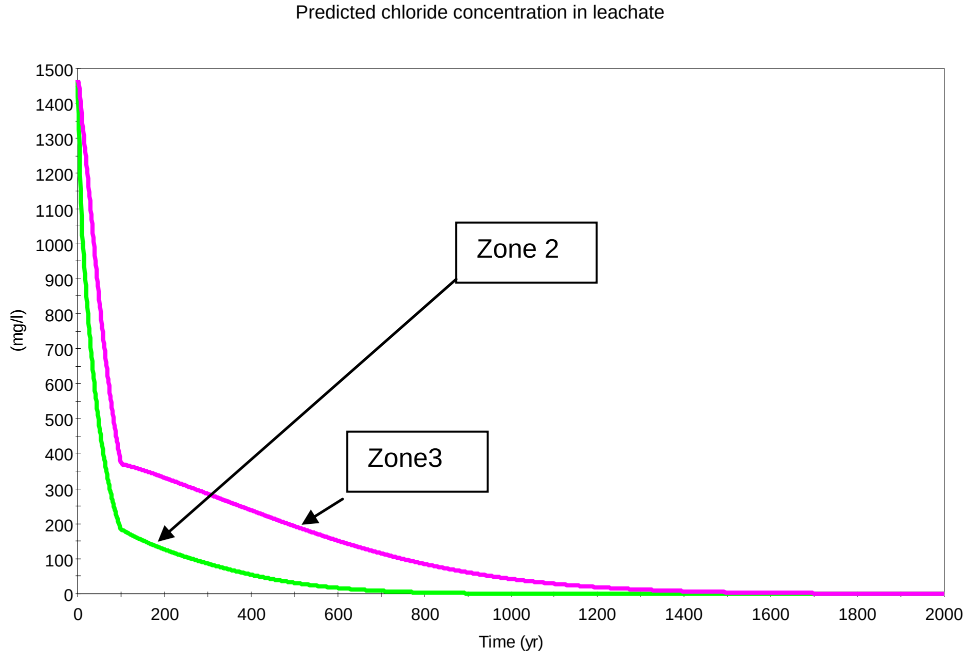
4.1 Introduction

In this section we report the results of the contaminant transport modelling undertaken using GoldSim. A large number of individual scenarios were modelled to assist in gaining an understanding of the sensitivity of the key design elements and controls on the resultant measure of sustainability.

The influence of the flow zones identified in the HBM model can be seen by examining the time history of leachate quality in the upper and lower saturated zones (Zone 2 and 3) within the Medium Depth MSW site shown in Figure 9.

In the scenario shown in Figure 9, the management time is assumed to be 87 years. At this point in time, the lower concentrations (which relate to Zone 2 in the upper and more heavily flushed part of the Site) are below the Drinking Water Quality Standard, while the upper line (which depicts the concentration in the lower part of the landfill – Zone 3) is well above the water quality standard. From time 0 to time 90 years there would have been only one leachate body as the Site would not start to flood until after the cessation of management control. The difference in leachate quality prior to the cessation of management control is simply the result of the shallower waste depth in the upper zone compared to the lower (and hence the ability to achieve a higher liquid/solid ratio even at early time). The two lines remain apart after the cessation of management control (after the marked change of slope) with the upper line not crossing the 250 mg/l concentration limit till 375 years. This change in slope is a direct result of the cessation of removal of leachate (one of the major controls to reducing the contaminant loading within the site).

Figure 9 Chloride Concentrations in Upper (Zone 2) and Lower (Zone 3) Parts of a Medium Depth MSW Landfill



4.2 Contaminant Migration Results

4.2.2 Groundwater Pathway Results

The full (detailed) results are not included in this summary but are shown in Tables 6a to 6e in the full report.

4.2.3 Surface Water Pathway Results

Concentrations of contaminants are reported after dilution in the "moat" surrounding the landfill. Dilution results from mixing the volume of overtopping leachate with (assumed) clean water that has originated as run-off from the cap.

The full (detailed) results are not included in this summary but are shown in Tables 7a to 7e in the full report.

The waste management community has, as a general rule, accepted the notion of leachate leakage through liner systems and the fact that leakage is probably proportional to the leachate head acting on the base of the Site. The mechanisms and controls on how this leakage is attenuated are understood to the extent that specialists are able to model and make predictions on the likely impacts, accepting that there is a good deal of uncertainty in the modelling process.

However, the industry has probably spent less time considering the controls that exist on the fate of leachate that has overflowed a liner system as a result of the cessation of management control. A discussion on these controls is therefore contained later in this report

4.2.4 Raw MSW Waste Stream (integrated results)

Based on the results obtained from mecoprop fails to meet prescribed standards at the base of the unsaturated zone (for List I substances) irrespective on how long a post closure management period is adopted. It should be noted that no account of biodegradation has been assumed for these model runs. Additional modelling has been undertaken to investigate the effectiveness of biodegradation in decreasing the impacts from this contaminant.

The deep landfill scenarios with MSW indicate that cadmium (another List I Substance) will also exceed its Minimum Reporting Value.

Ammoniacal nitrogen is an increasing problem with respect to groundwater as the sites become deeper. Only the shallow site geometry results in compliance with water quality standards should the Site be abandoned immediately after closure at 45 years.

Antimony is also identified as a potential problem at the deep site albeit that the degree of exceedance was minor (0.0053 mg/l against a standard of 0.005 mg/l). This should also be set against a background of limited leachate quality data in relation to Antimony.

The surface water results show a problem in relation to ammoniacal nitrogen only. While the degree of exceedance increases from the shallow to medium site geometry, the apparent marked reduction for the deep scenario needed further investigation. In the case of the deep site geometry the period during which overflow actually occurs is limited to a few years immediately following closure and prior to the liner degrading to the extent that it could no longer support a leachate head that was high enough to cause overflow. What is evident is that the deep scenario only just overflows and as such the volume of overflow is small compared to the overflow that is simulated for the shallow and medium geometry sites. Indeed it is so low that the available dilution is almost enough for compliance purposes.

Other contaminants meet their water quality standards, albeit that the concentrations (even after dilution) can exceed those for the List I substances at the base of the unsaturated zone. The reason being simply that for cadmium and mecoprop, the Freshwater EQS standards used are considerably more relaxed than the Minimum Reporting Standards used for compliance with the Groundwater Regulations. Note that where the EQS contains a range (usually related to the alkalinity of the water), a mid point has been taken between the minimum and maximum values. Arguably, the higher value should be taken given that leachates will contain a high level of alkalinity that would certainly increase the alkalinity of a poorly buffered stream, but we have opted to retain the "middle ground" approach.

4.2.5 MBT Residue Waste Stream (integrated results)

MBT residues contain fewer (if any) List I organic compounds. This demonstrates the importance of an aerobic treatment phase during waste pre-treatment. Mecoprop is not routinely found in MBT residues so have therefore not been modelled for this waste stream (Robinson et al, 2004).

Ammoniacal nitrogen is an increasing issue as the depth of the Site increases and cadmium becomes an issue for the deep site (the shallow and medium waste sites achieving compliance with respect to cadmium).

Surface water problems relate to ammoniacal nitrogen levels and (for the shallow and medium site geometries) copper. Part of the issue with copper is simply the very low compliance level (14 µg/l) compared to groundwater (2000 µg/l).

4.2.6 IBA Waste Stream (Integrated Results)

IBA wastes (because of their thermal treatment) do not contain many (if any) List I organic compounds. We have modelled solely the inorganic contaminants (including ammoniacal nitrogen). With respect to the groundwater pathway, there is a minor issue with cadmium for the deep site but all other contaminants fall below their limit values.

With respect to surface water there was a major non-compliance for copper where concentrations in the discharge from all but the deep landfill site were significantly in excess of the EQS based standards. Ammoniacal nitrogen was also an issue, but not a significant one.

The IBA deep and medium geometry land raise sites also have a problem with regards to copper and ammoniacal nitrogen in relation to the surface water discharge.

4.2.7 Sustainability Indicators

For those contaminants that have not met the groundwater and surface water standards after a management period of 45 years, the model has sought to determine the management time needed to ensure that when management is withdrawn, the discharges of that contaminant would meet the standard. The assumption is that by extending the management period, a larger proportion of the mass of individual contaminants would be directed to the leachate treatment plant, rather than be available for groundwater or surface water discharge. On the basis that one of the aspects of a sustainable landfill should be that the management period should be decades and not centuries, the management time gives a reasonable assessment of the sustainability of landfill.

For the majority of contaminants, the predicted maximum concentrations in the pathways were below the relevant water quality standards. It is therefore necessary to look only at those that failed to meet their relevant standards. Summary results are contained in Table 1.

Mecoprop causes all the MSW (groundwater pathway) runs to have management times in excess of 500 years, primarily because the concentration at the base of the unsaturated zone exceeds the MRV as a result of leakage that occurs during the managed phase of the landfill and hence lengthening the management period cannot assist in meeting this water quality standard. Even the model runs that included biodegradation of mecoprop failed to meet the water quality standard adopted for this contaminant in groundwater.

Copper is an issue in relation to surface water discharge for all the shallow and medium MBT and IBA scenarios. This is partly a function of the very low EQS for copper and, in the case of IBA, the relatively high concentrations of copper in leachate.

Table 1 Summary Results - Leachate Management Periods for Selected Scenarios

Scenario (Geometry, Waste, Configuration, and Cap)	Contaminant	Management Time Needed	
		Groundwater	Surface Water
Shallow MSW landfill with clay cap	Mecoprop	>500	<45
	Ammoniacal N	<45	200
Medium MSW landfill with clay cap	Mecoprop	>500	<45
	Ammoniacal N	105	240
Deep MSW landfill with clay cap	Mecoprop	>500	<45
	Ammoniacal N	325	50
	Cadmium	430	<45
Shallow MBT landfill with clay cap	Copper	<45	70
	Ammoniacal N	<45	305
Medium MBT landfill with clay cap	Copper	<45	65
	Ammoniacal N	160	325
Deep MBT landfill with clay cap	Ammoniacal N	365	60
	Cadmium	140	<45
Shallow IBA landfill with clay Cap	Ammoniacal N	<45	55
	Copper	<45	>500
Medium IBA landfill with clay Cap	Ammoniacal N	<45	206
	Copper	<45	>500
Deep IBA landfill with clay cap	Cadmium	250	<45
Medium IBA land-raise with clay cap	Ammoniacal N	<45	142
	Copper	<45	>500
Deep IBA land-raise with clay cap	Cadmium	<45	>500
	Ammoniacal N	<45	150
Shallow IBA landfill with clay cap and low grade composite sidewall liner	Copper	<45	387
	Ammoniacal N	<45	64
Medium IBA landfill with clay cap and low grade composite sidewall liner	Cadmium	315	No overflow
Shallow MBT Landfill with 1E-11 m/s liner	Ammoniacal N	<45	320
	Copper	<45	75
Shallow MBT Landfill with 1E-9 m/s liner	Ammoniacal N	150	110
	Cadmium	75	<45
Medium MSW Land-Raise	Mecoprop	250	<45
	Ammoniacal N	<45	200
Deep MSW Land-Raise	Mecoprop	250	<45
	Ammoniacal N	<45	230

4.3 Discussion of the Contaminant Modelling Results

Some general observations can be made from the results obtained so far in this study. Site geometry does play a key role in determining the route taken by contaminants as they are flushed from landfill.

On the premise that all liners leak, then all landfills will discharge leachate to groundwater. However, the degree of attenuation, the amount of dilution and the longevity of the discharge will be site specific issues albeit that the longevity of the discharge is itself partly related to the site geometry (as it controls the liquid/solid ratio). On the other hand, discharge to surface water is controlled by the depth of the landfill (or rim of the land raise site) and the amount of infiltration, leakage and timing of the cessation of management control. It is not inevitable except in shallow sites with high quality liners. However, the severity of the discharge is not reduced by attenuation mechanisms, only by dilution.

Table 2 Influences on Contaminant Fate in a Flooding Landfill

Waste Site Class	Factor	Discussion
Deep (landfill or land raise)	Smaller surface area	Affects dilution in groundwater due to small foot print.
Deep (landfill or land raise)	Smaller surface area	Smaller area generates less leachate.
Deep (landfill or land raise)	Smaller surface area	Longer time to reach same L/S ratio for same infiltration rate.
Deep (landfill or land raise)	Smaller surface area	Smaller amount of run-off for diluting surface discharges of leachate.
Deep (landfill)	Landfill overflow point	Head of leachate may not build up to a point where overflow occurs – all mobile contaminant must exit site via leachate treatment system and leakage to groundwater.
Deep (landfill)	Thick Zone 3	Deep sites will tend to have a larger stagnant zone compared to the more actively flushed Zones 1 and 2 that develop above and immediately below the level of saturation leading to lower concentrations being discharged to surface water (and conversely higher concentration to groundwater).
Shallow	Large Surface Area	Higher leachate production and hence high liquid/solid ratio achieved at earlier time.
Shallow Landfill and all Land Raise	Low overflow point	Virtually inevitable overflow upon cessation of management control.
Shallow Landfill and all Land Raise	Low overflow point	Zone 3 (stagnant area above liner) will be smaller and hence more rapid reduction in concentrations (but) equally less leakage due to lower leachate head so effect might cancel out.

Table 2 shows some of the significant controls that influence the degree of contamination flux directed to each of the pathways (and for completeness this includes the leachate treatment plant).

4.4 Fail-safe options

Four different fail-safe options have been examined in this report:

- Using waste site geometry;
- Using surface water drainage from the cap to dilute surface break-out of leachate;
- Adding an unmanaged wetland to polish the effluent from diluted surface run-off; and
- Modifying the sidewall liner system to utilise more of the unsaturated zone attenuation capacity while at the same time avoiding to an extent, the overtopping of leachate to surface water.

No single scenario worked for both groundwater and surface water in the same scenario. A number of the scenarios resulted in no groundwater breaches and some of the scenarios resulted in no surface water breaches but none worked for both.

Geometry plays an important role in partitioning the flow of contaminants from one pathway to the other – deep sites directing more leachate to groundwater with shallow sites directing more to surface water. However, there was no clear leader in the geometries studied.

The dilution of leachate in a surface water lagoon (receiving all run-off from the site) formed a basic part of each scenario and represents a minimum fail-safe option. However, ammoniacal nitrogen and copper were commonly well in excess of accepted quality standards in many of the overflowing scenarios. The addition of the a wetland polishing system did little to enhance this situation and while the treatment factors used may have been on the pessimistic side, it must be recalled that the wetland was an unmanaged wetland and therefore there must be some doubt firstly in the acceptability of relying on an unmanaged "living" treatment system.

The final fail-safe option showed some promise, but failed for IBA on copper and ammoniacal nitrogen discharges to surface water from a shallow site (albeit that the groundwater remained fully compliant, with the equivalent medium depth site (which did not overflow and hence has no surface water results) showed a failure in relation to cadmium (a List I substance) in relation to groundwater.

It is evident therefore that some form of intervention over and above the fail-safe engineering options used in this assessment is needed to render our solid waste sites a sustainable waste management option.

4.5 Discussion

In addition to the model runs undertaken to differentiate the effects of geometry and waste type, three model runs were undertaken to investigate the effects of liner hydraulic conductivity and a further four models run to investigate a fail-safe option of using a low grade side wall liner to attempt to limit the build-up of leachate and hence avoid overtopping while maximising the attenuation capacity of the unsaturated zone.

The findings of these model runs indicate that for mobile and readily flushed species such as chloride, a large proportion of the total chloride that will be mobilised will have been removed from the Site during its early operational and managed post closure period. A smaller proportion of ammoniacal nitrogen will have been released during the managed portion of the site's life, and hence more will be directed to groundwater and hence less to the LTP. Only a small proportion of immobile species such as cadmium will be released into the leachate prior to the post-managed portion of the site's overall life and therefore a far larger proportion will be available to leak from the base of the Site.

It is interesting to note, however, that the maximum concentrations predicted in the surface water pathway between the three different scenarios shows less than a factor of 2 between the highest concentrations (when the mineral liner is 1E-11 m/s) and lowest concentrations (when the mineral liner at 1E-9 m/s). Some of this can be attributed to that fact that there is no dispersion in the surface water pathway and the longer unsaturated zone travel time associated with the low hydraulic conductivity mineral liner scenario will lead to protracted travel times that will enhance the effectiveness of dispersion in groundwater. The role of dispersion in groundwater is often overlooked as being one of the attenuation mechanisms for highly retarded contaminants.

4.6 MSW Land Raise Model Runs

The land-raise models confirm the earlier findings that show that the limited head build up within a land-raise site combined with a good quality liner protects groundwater from the majority of contaminants. The only contaminant showing impact above the adopted groundwater standards used in this study (generally drinking water standards for List II substances and Minimum Reporting Values for List I substances) is mecoprop. However, it should be noted that we have not invoked any biodegradation of mecoprop within the modelling undertaken so far.

The surface water discharges from the land raise sites with MSW show large concentrations of ammoniacal nitrogen (24 and 30 mg/l, respectively, for the medium and deep scenarios) and well above the assessment level. In terms of the measure of sustainability, taken as the amount of time management would need to be continued in order to avoid this discharge, the period is 200 and 230 years, respectively. Such time periods are well beyond any definition of sustainable landfill. Mecoprop is not deemed to be an issue in the surface water discharge as its assessment criteria in surface water is above typical leachate concentrations.

4.7 Low Grade Sidewall Liner Model Runs

A series of model runs have been undertaken where a lower grade composite liner is used on the side slopes of the landfills (not land-raise sites) above 5 m above the base. This allows good containment of leachate during the managed period of site operation, but increases the leakage of leachate once management control is removed. The rationale is to gain more from the attenuation available from the purifying nature of the thicker unsaturated zone beneath the sidewalls and at the same time reduce the flux of contaminant that would be discharged to surface water. Such a fail-safe option would be best considered in areas where surface water discharge is less desirable than a groundwater discharge.

Modelling of additional fail-safe engineering options (specifically one where sidewall leakage is increased by using a low quality liner) indicated results from organic wastes that were little different from those with high quality liners. For the IBA waste stream, the increased leakage of contaminants that have low EQS values but that are well attenuated in the subsurface showed that the shallow scenario worked well with no exceedances of assessment criteria for groundwater. However, copper (and to a more limited extend ammoniacal nitrogen) remain an issue in the surface water discharge. Increased incineration forms part of the UK's waste strategy with an expected doubling of Energy from Waste capacity by 2020 (Defra 2007), and while IBA is not the only solid bi-product of incineration, it does form the larger part (circa 95%). The remaining solid residues result from fly ash and atmospheric pollution control residues and would be less likely to perform well in a landfill environment. Work is therefore needed to examine how copper can be removed from the surface water (preferably in a passive fail-safe manner) such that disposal to land can be made fully sustainable. In the experience of the author, copper has been identified as a problem in one Swedish Landfill where a treated discharge to surface water was authorised (with conditions), but breached even before wastes were accepted at the site. The site utilised selected IBA as a leachate drainage blanket and the copper in the discharge became a problem before waste was placed into the site.

5 Conclusions

Modelling of fail-safe engineering options (specifically one where sidewall leakage is increased by using a low quality liner) indicated results from organic wastes that were little different from those with high quality liners. For the IBA waste stream, the increased leakage of contaminants that have low EQS values, but that are well attenuated in the subsurface, showed that the shallow scenario worked well with no exceedances of assessment criteria for groundwater. However, copper (and to a more limited extend ammoniacal nitrogen) remain an issue in the surface water discharge. Increased incineration forms part of the UK's waste strategy with an expected doubling of Energy from Waste capacity by 2020 (Defra 2007), and while IBA is not the only solid bi-product of incineration, it does form the larger part (circa 95%). The remaining solid residues result from fly ash and atmospheric pollution control residues and would be less likely to perform well in a landfill environment. Work is therefore needed to examine how copper can be removed from the surface water (preferably in a passive fail-safe manner) such that disposal to land can be made fully sustainable.

What is clear is that engineering alone will not solve the problem of making landfill sustainable. Site management and operational practises along with robust liner systems are the only viable means of rendering landfill sustainable. Promising work has been published relating to the flushing of landfills and the injection of compressed air to oxidise those compounds that are resilient to degradation or flushing in anaerobic conditions. Work by Ritzkowski *et al* (2007) shows that at a small scale (laboratory lysimeters) there is a marked reduction of ammoniacal nitrogen concentration in leachate following a period of aeration. It might, therefore, be expected that a similar trend would be observed in a full scale trial. Observations at full scale showed the opposite effect with an increase in the concentration of ammoniacal nitrogen. The authors explain this phenomenon as a transient effect of mobilising leachate within the unsaturated parts of the landfill as a result of the air pressures used. While they state the effect is temporary, no evidence is presented to indicate the length of this temporary situation (which appeared to continue for in excess of 400 days). Certainly, if the mechanism for reducing the ammoniacal nitrogen concentrations in the laboratory is bacteriological oxidation, then there is no reason why this should not work in the field. Equally, if the reason for the continued increase is mobilisation of pore water in the unsaturated zone then that too must ultimately be reversible as the pore water is mobilised.

Waste properties that can influence the time needed to render a landfill benign have been discussed in broad terms in the main report. A view was taken at the sustainable landfill workshop, (March 2007 – see appendix 1) and is one that we concur with, that landfill remains the final disposal route for those residues generated by waste treatment processes, and provided the wastes generated by these processes are not hazardous waste then they will, inevitably, be placed into landfill.

Waste properties that are likely to have the largest bearing on sustainable landfill are the total leachable quantity, the rate of leaching and the density of the waste. Knowledge of these properties without addressing the issue of the disposal of waste processing residuals adds little to the debate. However, it must be noted, and was a point well made at the workshop that there is little incentive for operators of current landfills to spend money now to make their landfills more sustainable. While it is unlikely that most operators would specifically go out of their way to make their landfills less sustainable, it remains the case that unless they are required to manage wastes in a different way, or offered an incentive (by way of landfill tax relief) to undertake voluntary enhanced stabilisation, then the application of discounted cash flow will always make future management and remedial costs seem small compared to funding works now.

Equally, without demonstrating the actual functioning of a landfill that is operated in a sustainable manner utilising some, or all of the following it seems unlikely that the Industry or Government would have sufficient confidence to invest in a revised taxing system nor to undertake the relevant full scale demonstration that would allow proper evaluation of the differing management options:

- Pre-composting of all organic material entering the landfill (at least one aerobic phase);
- Flushing of wastes with water or treated leachate;
- Injection of air once the main LFG generation period has finished;
- Flooding the site to ensure hydraulic equilibrium is achieved and that both vertical and horizontal flow regimes have occurred within the waste mass (vertical during operation of the managed phase of the site and horizontal after flooding); or
- Post landfill mining and composting of residuals.

While not all of these options have been included in this study, the last 3 on the list above have yet to be well developed to the extent that rate constants can be derived to allow modelling of their effectiveness. The latter would always remain a final option should final stabilisation not be achieved at a specific site where an unacceptable impact was occurring. It would, however, be a very expensive option compared to the others unless the value of the mined waste became large enough to off-set the mining costs.

6 Recommendations for Further Work

While it is perhaps disappointing that at the end of this project no obvious fail-safe option appeared as a clear leader, it has highlighted some data gaps that exist which have hindered the research. Certainly, simple flushing of landfills, while beneficial, will not, in most cases, lead to sustainable landfill (although site specific factors will control this assumption to a degree).

The absence of rate constants that allow modelling of some of the processes that would assist in the assessment of whether landfill is sustainable has hampered this project. It would be good to be able to assign a value to the organic carbon and ammoniacal nitrogen removal efficiency of adding x Nm^3 of air per tonne of waste in place, or adding y kg of nitrate to a landfill (as a component of recycled but treated leachate).

A detailed cost benefit analysis is warranted using the type of discounted cash flow analyses used by operators so that the real costs and benefits can be understood by both sides. Into this analysis we would recommend including degradation of engineering systems that would need to be maintained in the longer term (so that the analysis is fair and not simply looking at deferred expenditure).

Further work on looking at passive systems for the removal of copper from the surface water system could also be advantageous. Anaerobic wetland treatment systems may be effective, but further research would be needed to quantify this. Such systems are effective at removing heavy metals from sulphate rich mine-waters although they are not truly passive in the long term, and will not have unlimited capacity for decades without some low cost maintenance. We believe that this is particularly needed in the light of Defra’s support for increased incineration to meet local authority biodegradable waste diversion targets. Removing copper (and cadmium) from the surface water pathway would open up some of the modelled scenarios to meet our definition of sustainable waste management.

In order to progress more detailed modelling using Napier’s HBM model, some fundamental research addressing the following issues would prove useful:

1) to corroborate, at large scale, the density dependent saturated moisture content and associated moisture profile(s).
2) to explore the effect of full saturation and/or high pore-water pressures on waste volume/settlement/strength and whether specific waste fractions might actually float.
3) to understand better the impact of moisture on waste strength - the hydrolysable matter.

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Additional thanks are also due to the delegates who attended the stakeholder workshop and gave their time, energy and intellect freely for the benefit of the project. There is a list of the delegates in Appendix 1 of the main report.

References

A list of references cited in this report are contained in the full report.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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