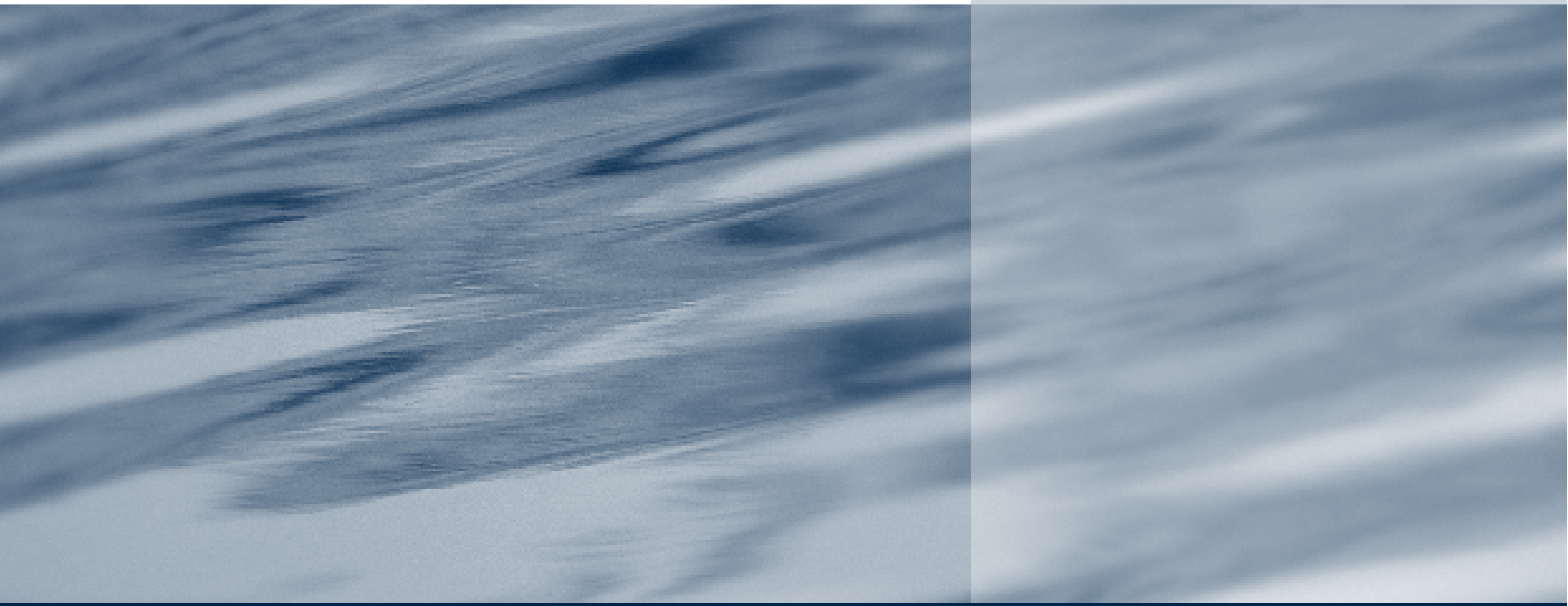

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Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0: User Manual

Science Report SC0310/SR

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This report is the result of research commissioned and funded by the Environment Agency's Science Programme.

Published by:
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
www.environment-agency.gov.uk

ISBN: 1844323153

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Dissemination Status:
Publicly available

Keywords:
Landfill, hydraulic containment, diffusion, sub-water table, risk assessment, contaminant flux

Research Contractor:
Environmental Simulations International Ltd, Priory House, Priory Road, Shrewsbury, SY1 1RU.

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Science Project Number:
SC0310/SR

Peer review and consultation:
This report was peer reviewed by Golder Associates.
A limited consultation was undertaken with industry, universities, consultants and the Environment Agency.

Product Code:
SCHO0904BIJD-E-P

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Professor Mike Depledge   Head of Science

CONTENTS

1 INTRODUCTION

This user manual has been prepared to assist users of the Environment Agency's *Contaminant fluxes from hydraulic containment landfills spreadsheet version 1.0.* It is complemented by the technical background for the spreadsheet in the report:

- Environment Agency, 2004a. *Contaminant fluxes from hydraulic containment landfills: a review. Science Report SC0310/SR*

This document describes the functionality of the spreadsheet and gives guidance on its use. It is not intended to describe the technical basis underpinning environmental risk assessment, the regulatory and policy context within which risk assessments are undertaken, or the Environment Agency's approach to assessing risk assessment reports (see Environment Agency, 2003a). The spreadsheet should only be used by suitably experienced risk assessors who are conversant with the relevant UK legislation, policy and guidance. It should be noted that there are a number of limitations to the model that make it a scoping tool rather than a full predictive model. If the appraisal of a risk assessment does not allow a clear decision to be made, more sophisticated modelling and/or well-constrained site specific data will be required.

The spreadsheet has been prepared for use in the Microsoft Excel 2000 environment. The file comprises about 450 KB and should not require any additional computing capability beyond that needed to run MS Excel. The spreadsheet has been tested in MS Excel 97, 2000 and XP but cannot be guaranteed to function in any other version of MS Excel.

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2 OVERVIEW

2.1 Background to Risk Assessment

The *Contaminant Fluxes from Hydraulic Containment Landfills Spreadsheet Version 1.0* computes diffusive contaminant fluxes from hydraulic containment landfills, and their concentrations in groundwater according to the technical basis presented in the report:

- Environment Agency, 2004a. *Contaminant fluxes from hydraulic containment landfills – a review. Science Report SC0310/SR*

A summary of the important processes identified and the relationships developed in the accompanying report (Environment Agency, 2004a) are presented here.

The spreadsheet has been developed to help risk assessors determine the potential for contaminant release from landfills operated on the basis of hydraulic containment. For risk assessment of conventional landfills – those with leachate heads higher than groundwater heads – several software tools such as LandSim are already available.

Readers who are unfamiliar with the concepts of environmental risk assessment, contaminant transport processes or the Agency's approach to protection of groundwater are directed to the following documents in the first instance, particularly the guidance on *Hydrogeological Risk Assessments for Landfills* (Environment Agency, 2003a).

- DETR *et al.*, 2000. *Guidelines for Environmental Risk Assessment and Management*. The Stationery Office.

- Environment Agency, 1998. *Policy and Practice for the Protection of Groundwater* (2nd Edition). The Stationery Office.

- Environment Agency, 2001a. *Guidance on the Assessment and Interrogation of Subsurface Analytical Contaminant Fate and Transport Models*. National Groundwater & Contaminated Land Centre Report NC/99/38/3.

- Environment Agency, 2003a. *Hydrogeological Risk Assessment for Landfills and the Derivation of Groundwater Control and Trigger Levels*. Report LFTGN01.

- Environment Agency, 2003b. *The Development of LandSim 2.5*. National Groundwater & Contaminated Land Centre Report GW/03/09.

This spreadsheet has application for groundwater risk assessments performed for existing or proposed landfill sites operated in settings where there is hydraulic containment. It may be used in support of other groundwater risk assessment tools used at the planning or landfill permitting stage. It may help to indicate whether a landfill can be engineered to comply with the EC Groundwater Directive (80/68/EEC), as implemented through the Pollution Prevention and Control Regulations 2000 and the Groundwater Regulations 1998.

Before selecting this or any other risk assessment model or tool, assessors should have developed a sound conceptual model of the site. They should be satisfied that the tool they select to model the site is appropriate, both in respect of representing the conceptual model and in performing analyses to a level that is appropriate to the quality of the input data. Guidance on these issues is provided in:

- Environment Agency, 2001b. *Guide to good practice for the development of conceptual models and the selection and application of mathematical models of contaminant transport processes in the subsurface*. National Groundwater & Contaminated Land Centre Report NC/99/38/2.

The development of a robust conceptual model is perhaps the most important aspect in the process of successfully estimating and evaluating environmental risks. The use of any mathematical modelling tool without first developing a robust conceptual model is likely to result in unreliable output. This spreadsheet should only be employed where a robust conceptual model has been developed, and the assessor is satisfied that the calculations performed by the spreadsheet are relevant to the processes described within that conceptual model.

Data quality is also a particular concern. Data used should be relevant, robust and derived from tests at the site, or otherwise shown to be relevant to the site. The provenance and relevance of all data included in an assessment using the spreadsheet should be documented by the assessor and included in the report(s) submitted to the Environment Agency for consideration.

It is important that the results produced with this spreadsheet are correctly interpreted. Further explanation is provided in Section 4. However, it is useful to note at this point that the spreadsheet should only be used to assess diffusive contaminant flux from hydraulic containment landfills. It is only one method in the toolbox to aid decision-making.

2.2 Mathematical Model

The basic mathematical model incorporated within the spreadsheet is illustrated by the schematic hydrogeological setting shown in Figure 1; there is a choice of three landfill construction scenarios which are described in Section 3.3 but they share common features of this hydrogeological setting.

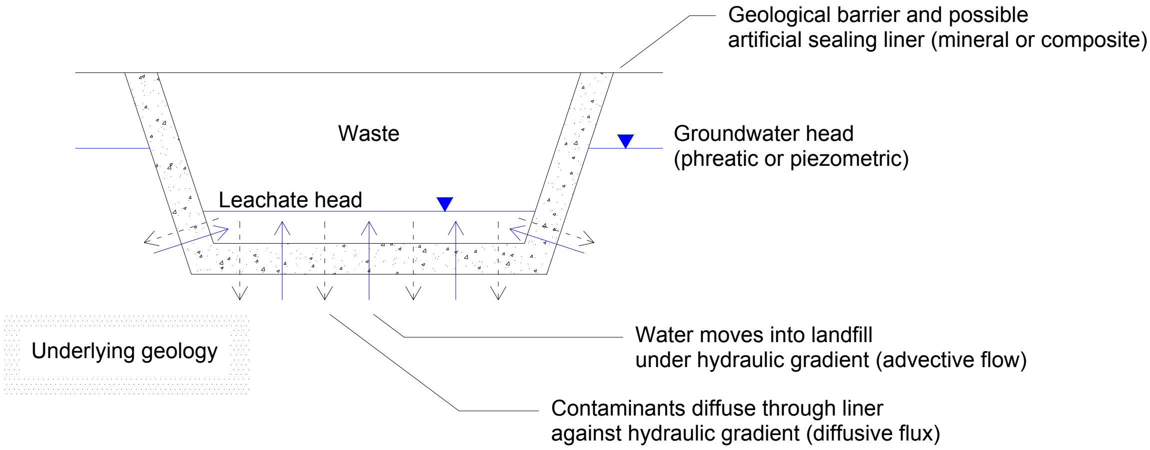


Figure 1. Basic conceptual model of a hydraulically contained landfill

It is important to note that the spreadsheet assumes that the landfill base is a flat (horizontal) surface upon which there is a uniform head of leachate, and the sides are steep (vertical). It assumes that there is a hydraulic gradient into the landfill, arising from a uniform external groundwater head. It assumes that the leachate head is controlled and remains constant over time.

A single chemical species in the leachate is considered and if more than one is of concern, multiple copies of the spreadsheet model will need to be maintained.

3 USING THE SPREADSHEET

The *Contaminant fluxes from hydraulic containment landfills spreadsheet v1.0* incorporates four worksheets, which have the following functions:

Introduction	Brief instructions; entry for site, contaminant and assessor details for transfer to subsequent sheets;
Scenario Selector	Allows selection between the three landfill construction scenarios presented in Section 3.3;
Calculations	Parameter value entry, calculations and presentation of the results including water and contaminant fluxes and contaminant concentrations
Justifications	Input of justification and references for user-defined parameters.

Data entry takes three forms. Each of the worksheets is password protected and data may only be entered in specific cells which are colour-coded yellow. Blue cells require selections to be made. Other cells are coloured grey or green and these are used to show interim and final calculation results respectively.

- Yellow cells require text or numeric data to be entered. Data should be site-specific, or literature data that are relevant to the site being considered. Field data and laboratory analyses should be obtained following a recognised good-practice method.

- Blue cells require selection of an option from a drop-down list. This allows the assessor to define the method of calculation according to the construction of the landfill, the contaminant type or the conceptual model.

- Interim results are presented in grey cells, while final calculation results are presented in green cells. These formulae are hard-coded and cannot be modified by assessors.

Note that all the screenshots in this section contain dummy values for contaminant transport parameters and these should not be used as a source of data.

3.1 Opening and Management of the Spreadsheet

On opening the spreadsheet in Excel 97, 2000 or XP a dialogue will indicate that there are macros in the spreadsheet and ask whether or not to disable them. The only macros in the spreadsheet as supplied are custom mathematical functions and will not harm your computer. The calculations on the spreadsheet will not run without macros enabled.

It is recommended that a copy of the spreadsheet be saved for each simulation as a distinct file.

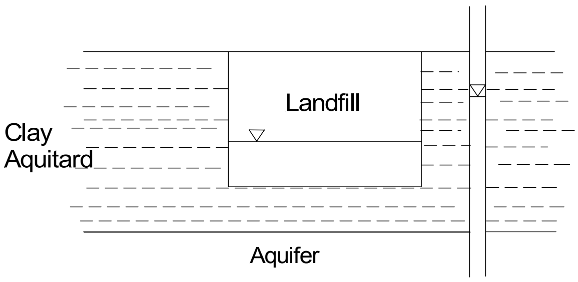
3.2 Introduction Worksheet

The first sheet is the *Introduction* worksheet. This contains brief instructions of data entry and three cells for entry of site information: site name, assessor's name and the date of the assessment. These data are automatically transferred to subsequent worksheets and are printed on the final versions. The spreadsheet will function without these data being entered, however, it is considered good practice to record assessment details and the Agency will expect any submitted assessments to include this information.

3.3 Scenario Worksheet

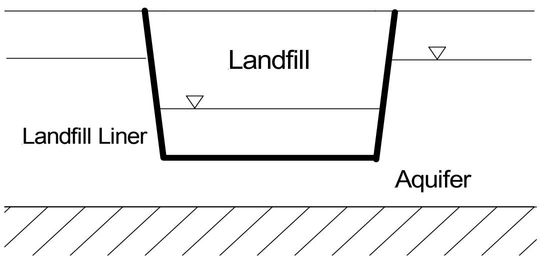
The *Scenario* worksheet allows the assessor to choose between three landfill construction scenarios that have been identified to be relevant for landfill sites operating in the UK and managed to provide hydraulic containment. The appropriate scenario for the landfill being assessed should be chosen from the following.

- A landfill without an artificial sealing liner, but which has been excavated in a low permeability clay stratum above a confined aquifer, (Scenario 1). This can also be used as a conservative approximation to simulate a new landfill site with an artificially constructed clay liner and *in situ* geological barrier by consideration of each component alone. This can be done by simulating the geological barrier alone (ignoring the mineral liner), and then comparing these results with a separate simulation of the mineral liner (assume the low permeability stratum does not exist). Alternatively, if the artificial clay liner is constructed from the same source as the *in situ* geological barrier, it may be appropriate to consider both layers together by assigning a composite value for the hydraulic conductivity.



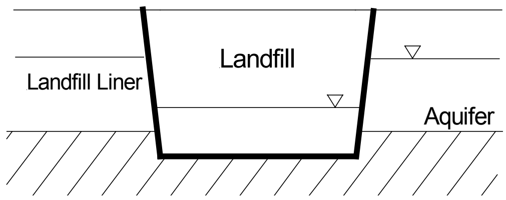
Scenario 1: a landfill without an artificial sealing liner in a low permeability formation.

- A landfill with an artificially formed geological barrier and artificial sealing liner [e.g. geomembrane composite, compacted clay or geosynthetic clay liner (GCL)] constructed wholly within a permeable formation, (Scenario 2).



Scenario 2: a landfill with a geological barrier and an artificial lining system in a permeable formation.

- A landfill with an artificially formed geological barrier and artificial sealing liner (e.g. geomembrane composite, compacted clay, GCL) constructed in a permeable formation but with a low permeability base, (Scenario 3). This scenario only considers the case where leachate levels are above the base of the aquifer. The pathways through the base of the landfill and then laterally back to the aquifer are neglected as less significant. If the leachate levels are maintained below the base of the aquifer in this setting, the system will afford better protection of the aquifer. If judged to be necessary, these reduced risks might be modelled using Scenario 1 to represent a pathway through the low permeability basal material back to the aquifer by an appropriate choice of effective thickness and area of the low permeability basal material comprising the pathway.



Scenario 3: a landfill with a geological barrier and an artificial lining system in a permeable formation but with its base on a very low permeability formation.

Figure 2. Typical hydrogeological settings for hydraulically contained landfills

3.4 Calculations Worksheet

The *Calculations* worksheet contains all the user parameter inputs, calculations and results from the model. This worksheet is divided into small sections where similar types of data should be input (Figure 3). Four columns are shown in the row for each parameter:

- the parameter description;
- its Excel name, used in the formulae (which can be viewed);
- the cell for entry of the parameter value, or where it is evaluated; and
- the units in which the parameter is used.

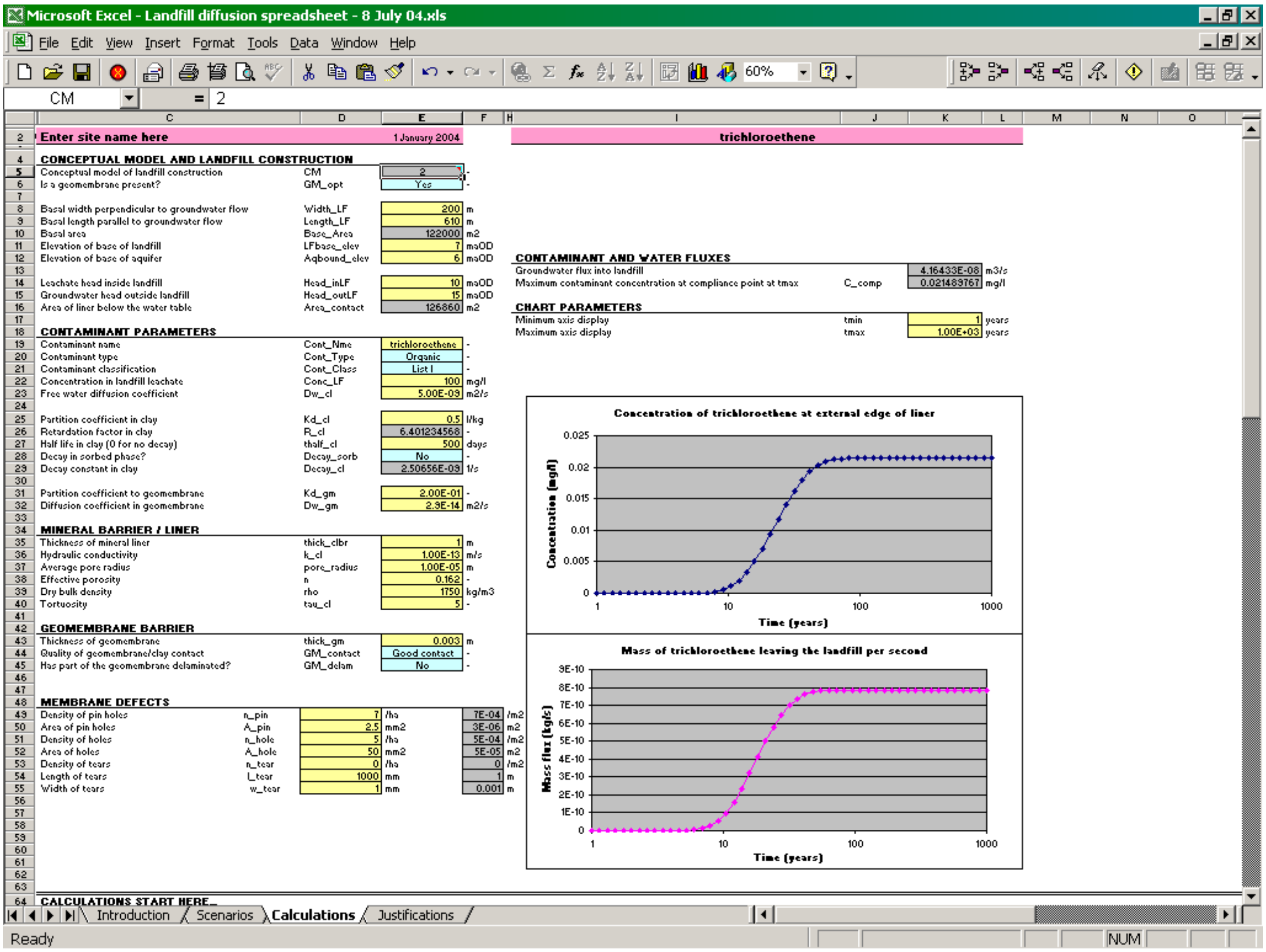


Figure 3. Location of data input and results sections on the *Calculations* worksheet

3.4.1 Conceptual Model and Landfill Construction

Inputs for this section include details of the dimensions of the landfill and the relative groundwater and leachate heads (Figure 4). If a composite liner is present, it is necessary to select “Yes” to indicate a geomembrane should be included. Values are required for the following parameters.

- **Basal width and length:** the landfill is assumed to be rectangular in shape. The length of the landfill is defined as the dimension parallel to groundwater flow, the width as the dimension perpendicular to the direction of groundwater flow.

- **Elevations:** all elevations and heads should ideally be entered as metres above Ordnance Datum (m AOD), but may be entered as metres relative to a site datum if Ordnance Datum levels are unavailable. Since most of the elevations in the model will vary across the site, and heads will vary spatially and over time, the appropriate effective values to be use will be uncertain. It is important that, when modelling, a number of scenarios are tested that simulate the likely range of parameter combinations that may be relevant.

Error flags highlight circumstances that are inconsistent with the mathematical model or geometry of the chosen scenario. If the worksheet shows an error flag no results will be displayed until the error is fixed. The following possible inconsistencies are tested:

- leachate head greater than groundwater head (all scenarios);

- leachate head and/or groundwater head below base of landfill (all scenarios);

- base of aquitard above base of landfill (Scenario 1);

- base of aquifer above base of landfill (Scenario 2);

- base of aquifer above leachate head (Scenario 3).

CONCEPTUAL MODEL AND LANDFILL CONSTRUCTION			
Conceptual model of landfill construction	CM	3	-
Is a geomembrane present?	GM_opt	Yes	-
Basal width perpendicular to groundwater flow	Width_LF	200	m
Basal length parallel to groundwater flow	Length_LF	610	m
Basal area	Base_Area	122000	m2
Elevation of base of landfill	LFbase_elev	0	maOD
Elevation of base of aquifer	Aqbound_elev	4	maOD
Leachate head inside landfill	Head_inLF	6	maOD
Groundwater head outside landfill	Head_outLF	10	maOD
Area of liner below the water table	Area_contact	3240	m2

Figure 4. ***Conceptual model and landfill construction*** **section**

3.4.2 Contaminant Properties

Inputs for this section include the name, classification (organic/inorganic, List I/List II) and physicochemical parameters for the contaminant of concern (Figure 5). If a geomembrane is present and the contaminant is organic, its properties in the geomembrane are entered here. Values are required for the following parameters.

- **Organic or inorganic substance:** organic substances diffuse through polymer geomembrane liners while inorganic substances do not. Mass flux of inorganic substances only occurs at geomembrane liner defects.

- **List I or List II substance:** these are defined by the Groundwater Directive and tabulated, for example, in Environment Agency (2003a). This determines the compliance point of the risk assessment. For a List I substance the compliance point is taken to be at the outer edge of the mineral barrier and the concentration in porewater at that point is reported. For a List II substance the compliance point is taken to be in the groundwater down hydraulic gradient from the site, and aquifer dilution can be taken into consideration.

- **Concentration in the leachate:** the leachate concentration is modelled as constant. In reality this will vary in time as leachate evolves and as groundwater flowing in through the liner and landfill cap dilutes it. An active gas extraction system will also tend to decrease the concentration of volatile organic compounds in the leachate. A suitable range of concentrations should be tested in the risk assessment.

- **Free water diffusion coefficient** of the contaminant: note that some references may refer to the effective diffusion coefficient, a combination of the free water diffusion coefficient and the tortuosity of the porous material tested (Environment Agency, 2004a). If a suitable effective diffusion coefficient is available this can be entered here but the tortuosity (entered as a property of the mineral barrier) must be assigned a value of one to ensure consistency.

- **Partition coefficient in the clay (mineral barrier/liner):** the retardation factor in the mineral liner is computed using a linear isotherm model, and the soil-water partition coefficient, K_d (ml/g), is used. For organic chemicals, unless site specific sorption data are available, it is most usual to compute the partition coefficient using the equation:

  $$K_d = K_{OC}.f_{OC} \qquad (1)$$

  where K_{OC} is the organic carbon-water partition coefficient
  f_{OC} is the fraction of organic carbon in the mineral liner

  This is discussed further in the accompanying report (Environment Agency, 2004a).

- **Half life in the mineral liner:** radionuclides will decay while within the liner system. Contaminants that biodegrade may do so in the liner, but site-specific evidence or measurements will generally be required to support this if it is relied upon in an assessment. If decay is not being modelled, input a very high value or zero (the spreadsheet understands that a zero value means ‘no decay’). A flag is used to set whether the contaminant degrades while sorbed (as will radionuclides) or not (if a contaminant can only be degraded while in aqueous solution).

- **Partition coefficient in the geomembrane:** describes how an organic compound partitions between water and the geomembrane; in some literature this is referred to as a solubility.

- **Diffusion coefficient in the geomembrane:** the effective diffusion coefficient of the contaminant in the geomembrane. A retardation factor for the geomembrane is not calculated as empirical diffusion coefficients obtained for organic chemicals in geomembranes include all attenuation processes. Nor is decay modelled in the geomembrane: organic compounds will not be degraded within the polymer as microbes cannot reach them, as the compounds are not in the aqueous phase.

In typical UK risk assessments it is common to use published data for most, if not all, of the parameters listed in this section. While the Environment Agency accepts that for some parameters, literature values will often be appropriate, it is essential that the use of literature values be completely justified in the context of each assessment. Environment Agency (2004a) presents indicative values for many of these parameters and references from which more may be obtained.

CONTAMINANT PARAMETERS			
Contaminant name	Cont_Nme	trichloroethene	-
Contaminant type	Cont_Type	Organic	-
Contaminant classification	Cont_Class	List I	-
Concentration in landfill leachate	Conc_LF	1000	mg/l
Free water diffusion coefficient	Dw_cl	5.00E-09	m2/s
Partition coefficient in clay	Kd_cl	0.5	l/kg
Retardation factor in clay	R_cl	6.401234568	-
Half life in clay (0 for no decay)	thalf_cl	500	days
Decay in sorbed phase?	Decay_sorb	No	-
Decay constant in clay	Decay_cl	2.50656E-09	1/s
Partition coefficient to geomembrane	Kd_gm	2.00E-01	-
Diffusion coefficient in geomembrane	Dw_gm	2.9E-14	m2/s

Figure 5. *Contaminant parameters* section

3.4.3 Mineral Barrier

Inputs for the *Mineral Barrier* section include hydraulic parameters of the mineral barrier beneath the landfill (Figure 6). For Scenario 1, this is the *in-situ* aquitard formation beneath the landfill and the thickness is automatically calculated from the elevations entered in the *Conceptual model and landfill construction* section. In Scenario 1, it is not possible to model the two mineral barriers, i.e. a mineral liner and the *in-situ* low permeability formation, together. However, if the two are present in a landfill being modelled, their impacts on contaminant attenuation can be compared by modelling both separately. For Scenarios 2 and 3 the *Mineral Barrier* is the mineral component of the liner system.

MINERAL BARRIER / LINER			
Thickness of mineral liner	thick_clbr	1	m
Hydraulic conductivity	k_cl	1.00E-11	m/s
Average pore radius	pore_radius	1.00E-05	m
Effective porosity	n	0.162	-
Dry bulk density	rho	1750	kg/m3
Tortuosity	tau_cl	5	-

Figure 6. *Mineral Barrier* section

Environment Agency (2004a) discusses in depth the use of these parameters in contaminant transport risk modelling of low permeability porous materials. The following comments may be made:

- **Hydraulic conductivity:** of the compacted mineral liner or *in-situ* very low permeability formation. Hydraulic conductivity varies with effective stress and it is up to the assessor to ensure that the hydraulic conductivity value used is appropriate for the thickness of waste to be emplaced. Often the reduction in hydraulic conductivity is related to the reduction in void ratio and may be computed using a variety of relationships (e.g. Das, 1995).

- **Pore radius:** of the compacted mineral liner. This is used to assign the value of hydrodynamic dispersion based on Taylor dispersion in a capillary tube (Section 2.3.7 in Environment Agency, 2004a). Higher values lead to more dispersion able to overcome higher inward velocities, so in the absence of site specific pore size data use an estimated high value consistent with laminar flow in the pores.

  If you are uncertain as to this mechanism, enter zero to neglect the process and consider using an increased effective porosity to reflect the fact that water flows more slowly at the edges of pores. Dispersion due to heterogeneity in the small-scale structure of the porous material is not modelled as it only applies to dispersion in the direction of flow (Section 2.3.6 in Environment Agency, 2004a).

- **Effective porosity:** as a fraction (by volume not by mass). In this context the effective porosity is that within which advection, diffusion and sorption processes operate and will probably be somewhat less than the total porosity (Environment Agency, 2004a). However, it is difficult to measure in practice and some sensitivity analysis will be required to address this uncertainty. Furthermore, porosity varies with effective stress (e.g. Rowe, 1998) and it is up to the assessor to ensure that the porosity value used is appropriate for the thickness of waste to be emplaced.

- **Dry bulk density:** of the compacted mineral liner.

- **Tortuosity:** the ratio of the true flow path of a particle through the porous material to the straight line flow path. Note that there are other definitions of tortuosity in the literature and care should be taken that the derivation of a tortuosity measurement is understood. There are few available data on tortuosity and this is best dealt with by sensitivity analysis. Furthermore, tortuosity varies with effective stress (Rowe, 1998) and it is up to the assessor to ensure that the tortuosity value used is appropriate for the thickness of waste to be emplaced.

3.4.3 Geomembrane Barrier

If a geomembrane is present (selected in the *Conceptual model and landfill construction* section) the *Geomembrane Barrier* section is visible (Figure 7). Here relevant parameters that describe the geomembrane are specified. The thickness of the geomembrane and the number and size distribution of defects are required input data. The assessor must also select the quality of contact between the geomembrane and the underlying mineral barrier. The following options are available.

- **Good contact:** defined in Giroud (1997) as 'good contact conditions correspond to a geomembrane installed, with as few wrinkles as possible, on top of a low-permeability soil layer that has been adequately compacted and has a smooth surface.'

- **Poor contact:** defined in Giroud (1997) as 'poor contact conditions correspond to a geomembrane that has been installed with a certain number of wrinkles, and/or placed on a low-permeability soil that has not been well-compacted and does not appear smooth.'

- **Delaminated**. Delamination occurs where heterogeneities in the waste allow high groundwater pressures to lift the geomembrane away from the mineral part of the composite liner. If this option is selected, the area of the liner that has delaminated should be defined. For this proportion of the area, no reliance can be placed on the geomembrane and only the mineral component of the liner will be used in calculations. It is assumed that any delamination due to loss of groundwater control during construction/initial landfilling has been repaired.

For landfills which were constructed under a good construction quality assurance (CQA) scheme, good contact can generally be expected. Older landfills where the CQA is not known or suspect will require a sensitivity analysis between both good and poor contact end points.

Other data required are:

- the density and dimensions of pin holes (0.1 – 5 mm^2) in the geomembrane,

- the density and dimensions of holes (5 – 100 mm^2) in the geomembrane, and

- the density and dimensions of tears (1 mm width x 100 – 10 000 mm length) in the geomembrane.

Data on the densities and dimensions of defects may be obtained from either of the following documents:

- Environment Agency, 2004b. *The likely medium to long-term generation of defects in geomembrane liners*. R&D Technical Report P1-500/1/TR.

- LandSim 2.5 manual.

GEOMEMBRANE BARRIER

Thickness of geomembrane	thick_gm	0.003	m
Quality of geomembrane/clay contact	GM_contact	Good contact	-
Has part of the geomembrane delaminated?	GM_delam	No	-

MEMBRANE DEFECTS

Density of pin holes	n_pin	12	/ha	0.0012	/m2
Area of pin holes	A_pin	2.5	mm2	2.5E-06	m2
Density of holes	n_hole	2.5	/ha	0.00025	/m2
Area of holes	A_hole	50	mm2	0.00005	m2
Density of tears	n_tear	0.5	/ha	0.00005	/m2
Length of tears	l_tear	1000	mm	1	m
Width of tears	w_tear	1	mm	0.001	m

Figure 7. *Geomembrane Barrier* section

3.4.5 Dilution

Where release of a List II substance is under consideration, allowance may be made for its dilution in groundwater flowing beneath the site. In the *Dilution* section the hydraulic conductivity and hydraulic gradient of the aquifer are entered so that the amount of dilution in the aquifer can be assessed (Figure 8). The dilution flux is computed using Darcy's Law, the width of the site and the mixing depth. The mixing depth is the minimum value of the saturated thickness of the aquifer or the depth of penetration of the contaminant into the aquifer. Various formulae are available to estimate the mixing depth and these are generally based on simple solutions to the advection-dispersion equation with a transverse dispersivity of 1% of the travel distance. For example, where there is no infiltration, Environment Agency (1999) gives the following relation in the context of contaminated land risk assessment:

$$z_{Mix} = \sqrt{0.0112x^2}$$

where z_{Mix} is the mixing depth (m)
x is the distance of the compliance point from the up-gradient edge of the landfill (m)

The formula in the *Dilution flow* cell (named *aq_Q*) may be over-written if the aquifer dilution is calculated by another means. A full justification will be expected if this option is used. However, the formula cannot be reset once it is over-written.

Normally the compliance point should be the down-gradient edge of the site to ensure that concentrations in groundwater leaving the site are acceptable. However for predictive purposes, for example if there are existing receptors away from the site, this distance can be varied.

STEADY STATE DILUTION			
Hydraulic gradient in the aquifer	aq_I	0.001	-
Hydraulic conductivity of the aquifer	k_aq	1.00E-05	m/s
Downgradient distance of compliance point from landfill	dist_cp	5000	m
Mixing width	Mix_W	200	m
Mixing depth	Mix_D	11	m
Dilution flow in aquifer directly under the landfill	aq_Q	0.000022	m3/s

Figure 8. *Dilution* section

3.4.6 Concentrations and Water Fluxes

The main results of the spreadsheet are presented in this section. The steady state water flux into the landfill is presented, and the maximum (in the selected time period – see *Time Variant Results* section) concentrations of the contaminant at the base of the low permeability barrier and at the List II compliance point (Figure 9).

No data entry is required for this section. Interpretation of these results is discussed in the next section.

CONTAMINANT AND WATER FLUXES			
Water flux into landfill		1.37088E-07	m3/s
Maximum contaminant concentration at compliance point at tmax	C_comp	0.215257105	mg/l

Figure 9. *Concentrations and Water Fluxes* section

3.4.7 Transient Results

Time evolution of the contaminant concentration and mass flux are displayed in this section of the worksheet (Figure C.10). The vertical (concentration or flux) axes are scaled automatically according to the results, but the horizontal (time) axis is scaled manually.

Minimum and maximum times for evaluation are set by the user; concentrations and mass fluxes are then computed between these limits and presented using a logarithmic time scale. It is important to identify an appropriate upper limit for the timescale that is sufficiently large that any contaminant breakthrough on timescales of concern is observed.

CHART PARAMETERS			
Minimum axis display	tmin	1	years
Maximum axis display	tmax	1.00E+03	years

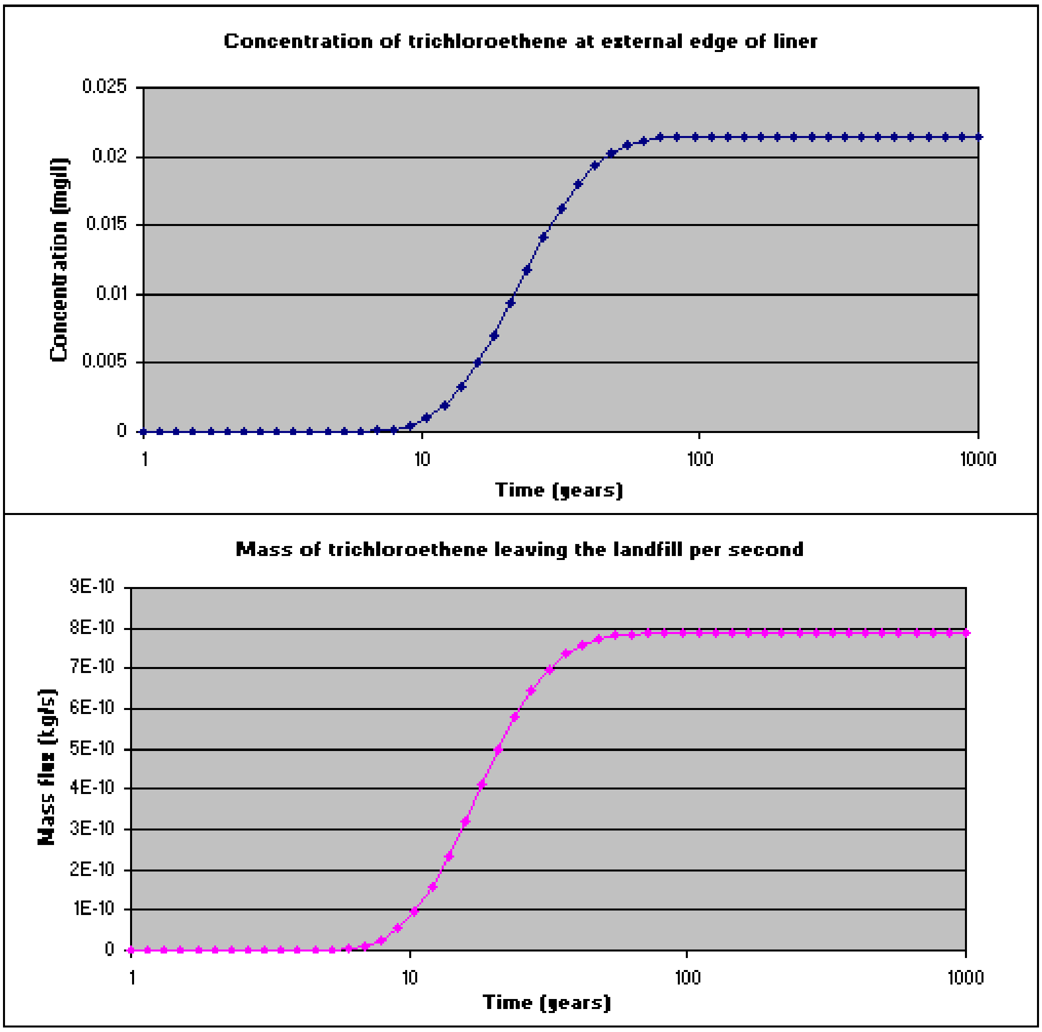
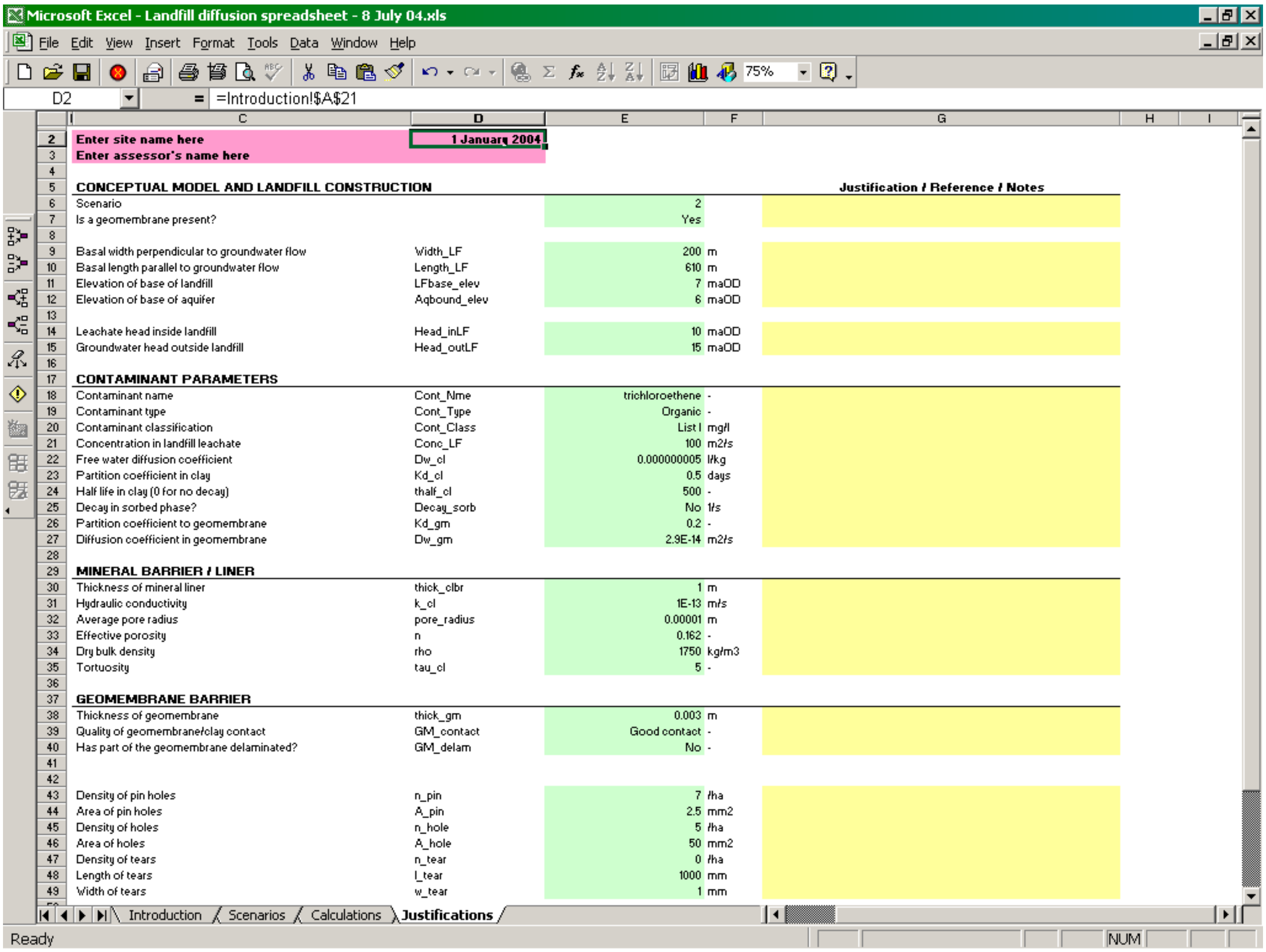


Figure 10. ***Transient Results*** **section**

3.5 Justifications Worksheet

The *Justifications* worksheet provides an area for justification or references for the parameters used in the *Calculations* worksheet. Values are copied across automatically from the *Calculations* worksheet so it is the user's responsibility to ensure that if the parameter value is changed, the justification is changed accordingly. The worksheet will function without these data being entered, however, it is considered good practice to record assessment details and the Agency will expect any submitted assessments to include this information.



Enter site name here		1 January 2004		
Enter assessor's name here				
CONCEPTUAL MODEL AND LANDFILL CONSTRUCTION				**Justification / Reference / Notes**
Scenario		2		
Is a geomembrane present?		Yes		
Basal width perpendicular to groundwater flow	Width_LF	200	m	
Basal length parallel to groundwater flow	Length_LF	610	m	
Elevation of base of landfill	LFbase_elev	7	maOD	
Elevation of base of aquifer	Aqbound_elev	6	maOD	
Leachate head inside landfill	Head_inLF	10	maOD	
Groundwater head outside landfill	Head_outLF	15	maOD	
CONTAMINANT PARAMETERS				
Contaminant name	Cont_Nme	trichloroethene	-	
Contaminant type	Cont_Type	Organic	-	
Contaminant classification	Cont_Class	List I	mg/l	
Concentration in landfill leachate	Conc_LF	100	m2/s	
Free water diffusion coefficient	Dw_cl	0.000000005	l/kg	
Partition coefficient in clay	Kd_cl	0.5	days	
Half life in clay (0 for no decay)	thalf_cl	500	-	
Decay in sorbed phase?	Decay_sorb	No	1/s	
Partition coefficient to geomembrane	Kd_gm	0.2	-	
Diffusion coefficient in geomembrane	Dw_gm	2.9E-14	m2/s	
MINERAL BARRIER / LINER				
Thickness of mineral liner	thick_clbr	1	m	
Hydraulic conductivity	k_cl	1E-13	m/s	
Average pore radius	pore_radius	0.00001	m	
Effective porosity	n	0.162	-	
Dry bulk density	rho	1750	kg/m3	
Tortuosity	tau_cl	5	-	
GEOMEMBRANE BARRIER				
Thickness of geomembrane	thick_gm	0.003	m	
Quality of geomembrane/clay contact	GM_contact	Good contact	-	
Has part of the geomembrane delaminated?	GM_delam	No	-	
Density of pin holes	n_pin	7	/ha	
Area of pin holes	A_pin	2.5	mm2	
Density of holes	n_hole	5	/ha	
Area of holes	A_hole	50	mm2	
Density of tears	n_tear	0	/ha	
Length of tears	l_tear	1000	mm	
Width of tears	w_tear	1	mm	

Figure 11. ***Justifications* worksheet**

4 DISCUSSION

4.1 Interpretation of the Results

4.1.1 Water flux into the landfill

To some extent this should have been reduced by the design of the landfill liner so that the operator does not have to treat more leachate than necessary or deplete the local groundwater resource. It can be easily understood that as the hydraulic conductivity and therefore velocity of water movement decreases, the resistance to contaminant diffusion is also reduced. An optimum hydraulic conductivity can therefore be chosen which minimises the water flux into the landfill, whilst ensuring that there is no unacceptable contaminant flux out of the landfill. Devlin and Parker (1996) show this in the context of a cut-off wall and computed an optimum hydraulic conductivity range of 10^{-10} to 10^{-8} m.s^{-1}.

Figure 12 shows an example calculated using the spreadsheet, using typical values for the other hydraulic properties of the mineral liner (with no geomembrane). Note, however, that the model does not take into account any effects of a more rapidly declining source due to increased flushing of the landfill at high hydraulic conductivities, nor does it take account of groundwater entering the landfill from above the specified leachate level. The spreadsheet is therefore likely to underestimate the total water flux into the landfill.

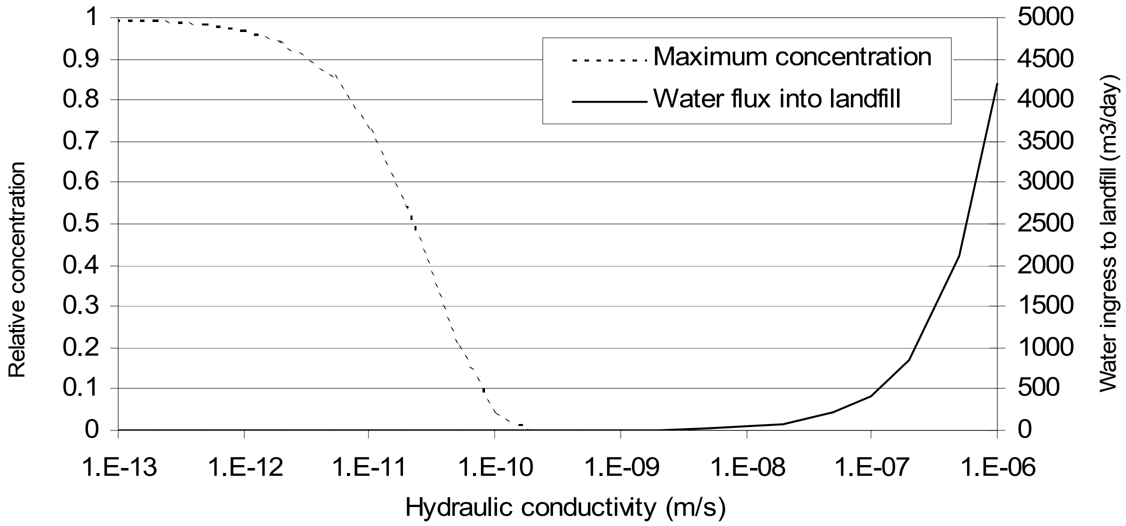


Figure 12. Trade-off between water influx and contaminant concentration at the liner edge (saturated hydraulic gradient across the liner = 0.2)

4.1.2 Boundary conditions

The spreadsheet models the transport of contaminants through the landfill barrier system, and specifies boundary conditions for this system. It does not include a detailed representation of the hydrogeological system beyond the outer edge of containment, which would often need to be site specific. The outer edge of the barrier system is not however a natural boundary for which exact boundary conditions can be specified for hydraulically contained landfills, and therefore approximations have to be used. In setting approximate boundary conditions, two alternative simplifications have been used in order to provide conservative calculations for List I and List II species respectively. These are as follows.

- A concentration of zero at infinity. This computes a conservative approximation to (i.e. over-estimate of) the concentration profile within the liner. This would normally be used for List I substances to calculate concentrations at the very base of the liner.

- A fixed concentration of zero at the outside edge of the liner. This is used to calculate a conservative bound to (i.e. over-estimate of) the diffusive contaminant flux through the liner. This flux can then be diluted with groundwater to give a concentration in groundwater. This would normally be used only for List II substances.

Section 4.3.3 of the accompanying report (Environment Agency, 2004a) presents a detailed discussion of these approximations. In summary, for List I substances, the plot of concentration at the outer edge of the liner is a conservative prediction of the presence of contaminants at the List I compliance point, and the plot of flux is presented for information only and for completeness of description of the solution. For List II substances the plot of contaminant mass flux is a conservative prediction. Consequently, the plot of concentration at the compliance point in the aquifer is also conservative. If, for a risk assessment of a List I substance, the contaminant flux is of interest in itself, the results for the solution evaluated for a List II substance should be considered. These outputs are discussed further in the following two points.

4.1.3 Maximum contaminant concentration for List II substances

The compliance point for the risk assessment is set at a different location depending on whether the contaminant is in List I or List II of the Groundwater Directive. For List I substances the compliance point is set at the base of the geological barrier. For List II substances the compliance point is set in the aquifer down hydraulic gradient of the landfill.

As discussed above this is derived using a solution that has a zero concentration set at the outer edge of the containment barrier. Clearly, this is inconsistent if the model then goes on to mix the outward contaminant flux with groundwater passing the edge of the liner and evaluating a corresponding non-zero concentration in groundwater. The approximation will always lead to an over-estimate of the concentration in groundwater, and in most cases where the landfill is not causing pollution this approximation will be acceptable. However if predicted concentrations are greater than approximately 10% of the leachate concentration, the approximation may begin to be less good leading to very conservative over-estimations of the concentration. This is highlighted on the spreadsheet and when this error message is displayed, the groundwater concentration *will* exceed 10% of the leachate strength, but the calculated concentration (greater than 10% of the leachate strength) cannot be relied upon as an accurate prediction of groundwater concentration. Indeed, for List II substances under certain hydrogeological conditions (i.e. little aquifer dilution), predicted concentrations may be unreasonable due to the inconsistency with the specified boundary condition and may even exceed the leachate concentration. For an accurate prediction of the magnitude of the groundwater pollution in these circumstances, a more sophisticated risk assessment involving treatment of the complete hydrogeological system may be required.

4.1.4 Mass flux of contaminant from landfill at maximum time for List I substances

This plot is shown for completeness of the presentation of the evaluated solution and should not be used in evaluating the risk of discharge of List I substances.

At points along the contaminant transport pathway, the mass flux peaks after the breakthrough as initial concentration gradients within the liner are steep. This is only temporary and as time progresses the concentration gradients reach steady state and the mass flux stabilises (Figure 13). The reported mass flux is therefore that evaluated over most of the lifetime of the landfill. However, this is not a conservative result for List I substances where the appropriate measure of the contaminant discharge is the concentration at the outer edge of containment. The transient peak will generally be an underestimate of real fluxes through the outer edge of containment. If the flux is of interest, it can be calculated by selecting the calculation for a List II substance with identical contaminant transport properties and considering the flux plot (the concentration plot will incorporate dilution in the receiving groundwater which should not be taken into account when considering the release of List I substances).

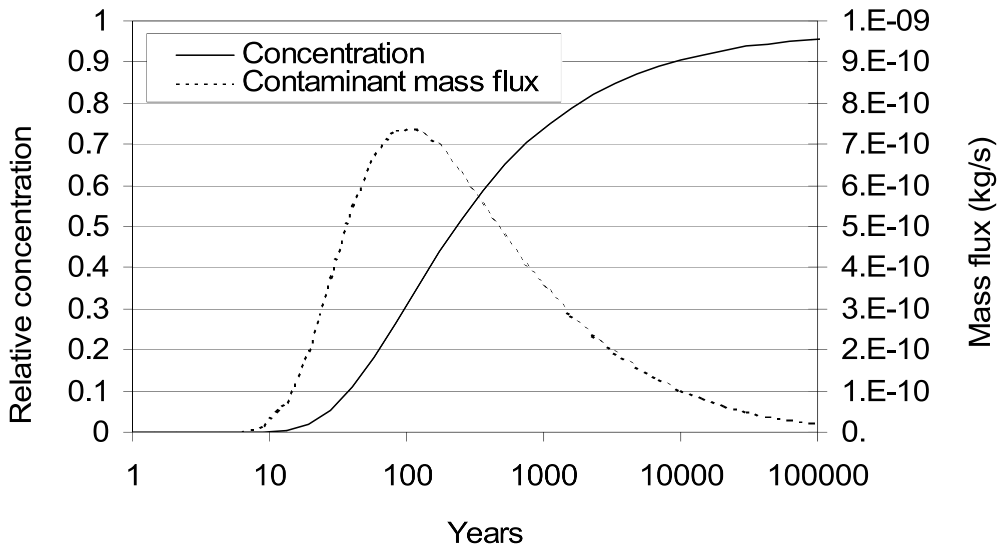


Figure 13. Breakthrough concentration and contaminant mass flux at the base of a landfill with a compacted clay liner

4.1.5 Transient results

Breakthrough times on the chart of time variant results only show the time taken for the contaminants to diffuse across the liner system. It does not take account of advective travel time through the aquifer nor the diffusive travel time through a geomembrane defect (if a geomembrane is present). No account is taken of any leakage of leachate during the initial stages of landfill construction and filling when the aquifer is dewatered and the landfill is above the water table. These breakthrough curves should not therefore be taken as predictive of contaminant breakthrough times.

4.1.6 Movement of organic solutes through composite liners

Environment Agency (2004a) discusses how, for organic solutes in composite liners, advective flow beneath defects limits concentrations at the base of the liner whereas beneath intact geomembrane, the contaminant freely diffuses through the static water column. Figure 14 shows the variation in solute concentrations and water ingress to an example landfill with a composite lining system. As the number of defects increases, it is seen that organic concentrations decrease whilst inorganic concentrations increase. The former occurs because the advective flux influences more of the area of the liner, resisting migration of the organic species (which is otherwise diffusing through intact geomembrane and static water beneath). Inorganic concentrations increase because there are more defects in the geomembrane through which they can diffuse. Up to a certain threshold, organic concentrations show a regular decrease with an increase in the number of defects. However, between 16 and 17 pin-holes per hectare, the resultant concentration drops dramatically. This corresponds to the point at which the zones of influence of each defect coalesce and all contaminant movement through the mineral liner is inhibited by inward advective flow.

In reality, this will be a more gradual transition, since advective velocities decrease radially out from the defect, and when they first begin to overlap, the inward velocity in the overlap zones will be small. The extent to which organic contaminants are inhibited from outward migration will therefore continue to increase progressively as the low-inward-velocity zones associated with the defects overlap and superpose. The model, however, shows a sharp transition from immobile water beneath areas of intact membrane outside the zones of influence of any defect, and applies an average inward velocity throughout the zones of influence of all defects, hence the sharp transition.

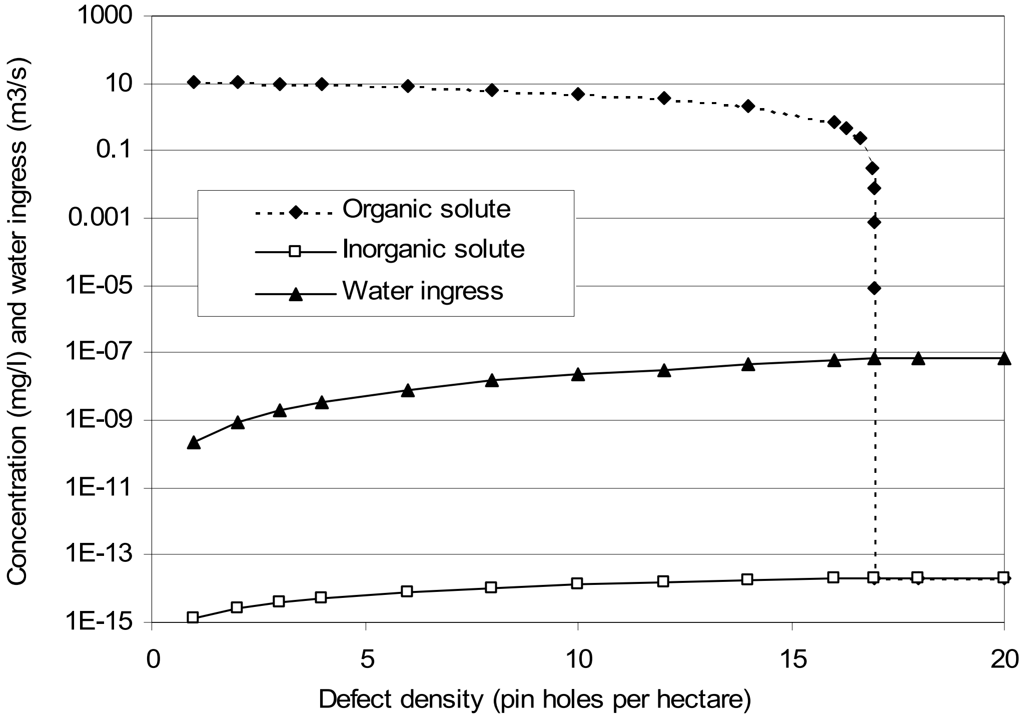


Figure 14. Variation of external solute concentrations with geomembrane quality

4.1.7 Oscillations and numerical accuracy

The numerical evaluation of the solution is robust but for some combinations of parameters, small oscillations are seen in the breakthrough plots. These arise when the breakthrough involves sharp fronts and are a well known phenomenon for the solution of diffusive problems. They occur particularly where diffusion occurs with degradation. Small oscillations can be ignored, but if they are significant at the level of decision making, more accurate calculations should be undertaken with more sophisticated risk assessment tools using more computationally intensive Laplace transform solvers such as Talbot's method.

4.2 Limitations of the Model

It should be noted that there are a number of limitations to the model that will generally make it a scoping tool rather than a detailed final risk assessment model. It uses a generic mathematical model rather than representing the site specific conceptual model explicitly. If the appraisal of a risk assessment does not allow a clear decision to be made, more sophisticated modelling and/or well-constrained site specific data will be required.

Additionally, a number of simplifying approximations have been made in the calculations that must be confirmed as relevant for the site-specific conceptual model. It is not possible to predict definitely whether or not these are conservative assumptions but generally the consequence of these limitations will be either conservative or small. If it is not clear how important these limitations are for the site under consideration, expert advice should be sought.

- As is conventional in UK landfill risk assessment tools, the mathematical model solves for contaminant transport along one-dimensional pathways. In particular for composite lined landfills, a one-dimensional pathway is used to represent the leakage flow path and outward migration against this flow. See Rowe (1998) for further discussion.

- The water balance for the landfill is assumed to be steady state. It takes no account of deterioration of the liner through time either by desiccation of the clays or by damage and oxidation of the geomembrane (Environment Agency, 2004b).

- Since the model is designed primarily to compute contaminant transport, it does not account for any groundwater that might seep into the unsaturated waste above the level of the leachate head. The water flux into the landfill from groundwater may therefore be slightly higher than predicted due to this component of inflow. Infiltration through the landfill cap is also not considered.

- Neither the water balance nor the contaminant transport calculations account for a period of above water table operation during construction and initial filling of the landfill. If leachate leakage occurs during this initial phase its breakthrough at a compliance point will not be predicted by this model.

- No estimate is made for the time to exhaust the cation exchange capacity in the mineral liner, as described in Environment Agency (2002); the model assumes that it is never exhausted. If separate calculations show that this would occur at times of concern (after taking into consideration possible decline of the leachate source) then the linear isotherm partition coefficient (K_d) will not be appropriate and unretarded transport should be considered.

- The leachate concentration is assumed to remain constant over time. In reality this will decrease in time as leachate evolves and as groundwater flowing in through the cap and the liner dilutes it. This assumption may therefore be very conservative.

- No account is taken of diffusion coefficients increasing with temperature. If elevated temperatures are anticipated for the lifetime of the landfill, an Arrhenius relationship may be used to scale the diffusion coefficient of a solute (Langmuir, 1997).

- No account is taken for the membrane effects of clayey materials (e.g. osmosis, anion exclusion or steric hindrance).

- No account is taken of the degradation of liner materials with time.

- Contaminant transport in underlying geological formations is not modelled.

- The predicted concentration of List II contaminants in groundwater are calculated for discharge of List II substances mixed with groundwater flowing beneath the site and assumed to mix with all groundwater to an estimated mixing depth. This does not take into account any localised areas of greater discharge or the design of monitoring wells. Therefore whilst predicting compliance of the site with Groundwater Regulations in the context of pollution due to discharge of List II substances, observations at specific monitoring wells may be influenced by their specific setting and completion which should be considered in setting control and trigger levels.

- No explicit consideration is made of the natural background concentrations and the predicted discharges will be reduced if there is significant background contamination. This can be considered by setting the leachate concentration to the excess contaminant concentration above the background (and interpreting the resulting calculated concentrations as additional excess contaminant concentration above background levels).

This approach neglects the time for concentrations in the lining material to rise to the level of the surrounding natural background. Thus, the model calculations can be interpreted as assuming that the system is initially saturated with water at the background concentration and having calculated the additional impact of the excess concentration in the leachate.

- It is assumed that the leachate drainage and collection layer is present and effective, and therefore there is assumed to be no risk due to perched layers of leachate in contact with the lining system above the external groundwater level leading to outward advective transport pathways. It is further assumed that the leachate collection system does not allow significant leachate mounds to develop away from the leachate collection points and that the specified leachate head is an appropriate value across the entire cell or phase being modelled (for example this may be a concern if the site has only perimeter leachate collection drains and the leachate head might then exceed groundwater heads in the middle of the site leading to a loss of hydraulic containment).

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APPENDIX 1. WORKED EXAMPLES

A series of 6 worked examples has been developed using the spreadsheet created as part of the project (NC/03/10/TR) *Contaminant fluxes from hydraulic containment landfills* – a review.

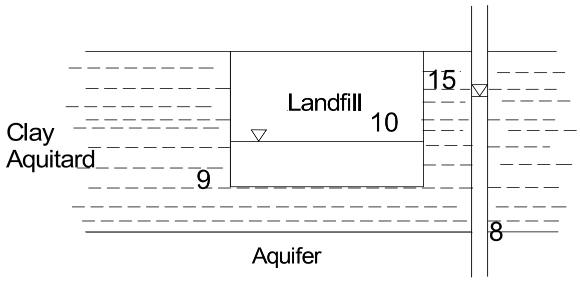
The input values for these worked examples are summarised below. They have been taken from a literature review and experience at typical landfills, and have been chosen to illustrate how the spreadsheet works, and how the results may be interpreted. These examples are not intended to cover every possible site, and should not be considered to represent "default" values or an "acceptable" landfill design.

The sources of the parameter values used are reported in the "Justifications worksheet". For these worked examples, the default landfill size and setting are (the complete set of input values and results are provided in the spreadsheets that accompany this User Manual):

Width = 200m	Length = 610m
Groundwater elevation = 15m AOD	Leachate elevation = 10m AOD
Landfill base = 9m AOD (i.e. leachate head = 1m)	Thickness of mineral barrier/liner = 1m
Hydraulic conductivity of mineral barrier/liner = $1x10^{-9}$ m/s	Hydraulic conductivity of aquifer = $1x10^{-5}$ m/s

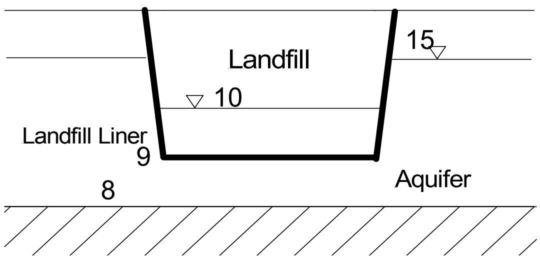
Scenario 1: A landfill without an artificial sealing liner in a low permeability formation

1.1 – List I Cadmium – leachate concentration = 1.01 x 10^{-2} mg/l
1.2 – List II Chloride – leachate concentration = 1140 mg/l



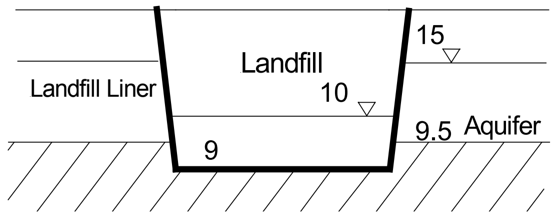
Scenario 2: A landfill with a geological barrier and an artificial lining system (including a geomembrane) in a permeable formation

2.1 – List I Cadmium (inorganic) – leachate concentration = 1.01 x 10^{-2} mg/l
2.2 – List I Trichloroethene (organic) – leachate concentration = 5.6 x 10^{-3} mg/l



Scenario 3: A landfill with a geological barrier and an artificial lining system (including a geomembrane) in a permeable formation but with its base on a very low permeability formation

3.1 – List I Trichloroethene (organic) – leachate concentration = 5.6 x 10^{-3} mg/l
3.2 – List II Ammonium (inorganic) – leachate concentration = 723 mg/l



A.1 Interpretation of results and sensitivity analysis.

Scenario 1 – worked example 1.1. Cadmium (List I inorganic contaminant)

Worked Example 1.1* Leachate concentration = 1.01 x 10^{-2} mg/l Target concentration = 1 x 10^{-4} mg/l	Maximum concentration at compliance point (mg/l)	Groundwater flow into landfill (m^3/s)	Breakthrough time to maximum concentration (years)	Comment
Default case (1.1.xls)	1.4 x 10^{-40}	1.2 x 10^{-3}	2,291	Acceptable risk
Change to hydraulic conductivity of mineral barrier k = 1 x 10^{-10} m/s (EG1.1a.xls)	1.7 x 10^{-6}	1 x 10^{-4}	50,119	Decreased groundwater inflow leads to greater outward flux of contaminants but increased time to maximum concentration. Acceptable risk
Change to hydraulic conductivity of mineral barrier k = 1 x 10^{-8} m/s (EG1.1b.xls)	0	1.2 x 10^{-2}	0	Increased groundwater inflow prevents breakthrough of contaminants. Greater volumes of leachate generated. Acceptable risk
Hydraulic conductivity of mineral barrier = 1 x 10^{-9} m/s Groundwater - leachate head difference = 0.1 m (EG1.1c.xls)	1.8 x 10^{-3}	2.4 x 10^{-5}	~12,000 till > target concentration	Decreased groundwater inflow leads to increased maximum concentration at compliance point. Probable unacceptable risk.
Hydraulic conductivity of mineral barrier = 1 x 10^{-10} m/s Groundwater - leachate head difference = 0.1 m (EG1.1d.xls)	8.5 x 10^{3}	2.4 x 10^{-6}	>1,000,000	Decreased groundwater inflow leads to increased maximum concentration at compliance point but not until >7,000 years. Potentially unacceptable risk.

** default conditions apply unless stated.*

Note: The number of significant figures reported is for illustration and not because there is such a high level of confidence in the results.

The results suggest that for cadmium in Scenario 1, each of the considered designs is likely to be acceptable although there is a greater risk associated when very small (0.1 m) head differences are considered. The minimum risk appears to be when the hydraulic conductivity of the mineral barrier is increased to 1 x 10^{-8} m/s, however this must be balanced against increased leachate volumes being generated and potential stability issues.

Scenario 1 – worked example 1.2. Chloride (List II inorganic contaminant)

Worked Example 1.2* Leachate concentration = 1140 mg/l Target concentration = 250 mg/l	Maximum concentration at compliance point (mg/l)	Groundwater flow into landfill (m^3/s)	Breakthrough time to maximum concentration (years)	Comment
Default case (EG1.2.xls)	3 x 10^{-10}	1.2 x 10^{-3}	5	Acceptable risk
Change to hydraulic conductivity of mineral barrier k = 1 x 10^{-10} m/s (EG1.2a.xls)	33.5	1.2 x 10^{-4}	48	Decreased groundwater inflow leads to greater outward flux of contaminants but increased time to maximum concentration. Acceptable risk
Change to hydraulic conductivity of mineral barrier k = 1 x 10^{-8} m/s (EG1.2b.xls)	1.4 x 10^{-129}	1.2 x 10^{-2}	<1	Increased groundwater inflow prevents breakthrough of contaminants. Greater volumes of leachate generated. Acceptable risk
Hydraulic conductivity of mineral barrier = 1 x 10^{-9} m/s Groundwater - leachate head difference = 0.1 m (EG1.2c.xls)	>10% leachate concentration	2.4 x 10^{-5}	Error	Error message since contaminant concentration at compliance point predicted to be >10% of leachate concentration. Model results unreliable but likely to be unacceptable risk – use different model.
Hydraulic conductivity of mineral barrier = 1 x 10^{-10} m/s Groundwater - leachate head difference = 0.1 m (EG1.2d.xls)	>10% leachate concentration	2.4 x 10^{-6}	Error	Error message since contaminant concentration at compliance point predicted to be >10% of leachate concentration. Model results unreliable but likely to be unacceptable risk – use different model.

** default conditions apply unless stated.*

Note: The number of significant figures reported is for illustration and not because there is such a high level of confidence in the results.

The results indicate that for chloride in Scenario 1, if the head difference between the leachate and groundwater is too small, the diffusive flux is too great and the model results become unreliable. This is because for List II substances, the model sets the concentration at the outer edge of the mineral barrier equal to zero to give a conservative estimate of the concentration in groundwater. In most cases where the landfill is not causing pollution, this approximation will be acceptable but if the predicted concentrations are greater than approximately 10% of the leachate concentration, the approximation becomes overly conservative (see section 4.1.3 above for explanation). Also, as the hydraulic conductivity of the mineral barrier is decreased, the risk increases, although it is likely to be acceptable for typical designs.

Scenario 2 – worked example 2.1. Cadmium (List I inorganic contaminant)

Worked Example 2.1* Leachate concentration = 1.01×10^{-2} mg/l Target concentration = 1×10^{-4} mg/l	Maximum concentration at compliance point (mg/l)	Groundwater flow into landfill (m^3/s)	Breakthrough time to maximum concentration (years)	Comment
Default case (EG2.1.xls)	8.2×10^{-18}	4.5×10^{-7}	6,918	Acceptable risk
Remove geomembrane (EG2.1a.xls)	1.4×10^{-40}	6×10^{-4}	2,500	Increased groundwater inflow decreases maximum concentration at compliance point, but removal of geomembrane decreases time to breakthrough. Greater volumes of leachate generated. Acceptable risk

** default conditions apply unless stated.*

Note: The number of significant figures reported is for illustration and not because there is such a high level of confidence in the results.

The spreadsheet predicts that for cadmium, both designs for the landfill are acceptable, although the risk is lower without a geomembrane present, however this situation would result in increased volumes of leachate being generated.

Scenario 2 – worked example 2.2. Trichloroethene (List I organic contaminant)

Worked Example 2.2* Leachate concentration = 5.6×10^{-3} mg/l Target concentration = 1×10^{-4} mg/l	Maximum concentration at compliance point (mg/l)	Groundwater flow into landfill (m^3/s)	Breakthrough time to maximum concentration (years)	Comment
Default case (EG2.2.xls)	5.5×10^{-3}	4.5×10^{-7}	40 (till >target concentration)	Unacceptable risk
Remove geomembrane (2.2a.xls)	9.6×10^{-42}	6.2×10^{-4}	9	Removal of geomembrane decreases outward diffusive flux. Greater volumes of leachate generated. Acceptable risk
Default case but with degradation of TCE (EG2.2b.xls)	1.3×10^{-7}	4.5×10^{-7}	48	The degradation rate of TCE within the liner is sufficient to counter the diffusive flux through the intact geomembrane. Acceptable risk

** default conditions apply unless stated.*

Note: The number of significant figures reported is for illustration and not because there is such a high level of confidence in the results.

The lower risk predicted by the removal of the geomembrane in example 2.2a is perhaps counter-intuituive. Trichloroethene partitions into, moves through, then partitions back out of the geomembrane (HDPE in this example) and into the porewater in the mineral liner through which it is transported by diffusion. Water cannot pass through the intact geomembrane, and so this outward diffusive flux is not counteracted by inward advective flow, except beneath defects (through which water can pass into the landfill). Therefore, an intact geomembrane is predicted to allow a greater flux of organic contaminants out of the landfill than is calculated from a mineral liner alone.

Example 2.2b illustrates that if degradation can be considered for organic contaminants, then for the parameter values used in this example, this will tend to counter the impact of the outward diffusive flux through the intact geomembrane. If different parameter values are chosen (particularly the degradation rate), then this may not be the case. It should be noted that the spreadsheet predicts a steady-state flux after 40 years since the source-term concentration is constant and degradation is only modelled during transport through the liner.

Scenario 3 – worked example 3.1. Trichloroethene (List I organic contaminant)

Worked Example 3.1* Leachate concentration = 5.6 x 10^{-3} mg/l Target concentration = 1 x 10^{-4} mg/l	Maximum concentration at compliance point (mg/l)	Groundwater flow into landfill (m^3/s)	Breakthrough time to maximum concentration (years)	Comment
Default case (EG3.1.xls)	5.6 x 10^{-3}	2.9 x 10^{-9}	40 (till >target concentration)	Unacceptable risk
Remove geomembrane (EG3.1a.xls)	9.6 x 10^{-42}	4 x 10^{-6}	9	Removal of geomembrane decreases outward diffusive flux. Greater volumes of leachate generated. Acceptable risk
Default case but with degradation of TCE (EG3.1b.xls)	1.3 x 10^{-7}	2.9 x 10^{-9}	48	The degradation rate of TCE within the liner is sufficient to counter the diffusive flux through the intact geomembrane. Acceptable risk
** default conditions apply unless stated* *Note: The number of significant figures reported is for illustration and not because there is such a high level of confidence in the results.*				

The model results are very similar for Scenario 3 and Scenario 2 for TCE.

Scenario 3 – worked example 3.2. Ammonium (List II inorganic contaminant)

Worked Example 3.2* Leachate concentration = 723 mg/l Target concentration = 0.5 mg/l	Maximum concentration at compliance point (mg/l)	Groundwater flow into landfill (m^3/s)	Breakthrough time to maximum concentration (years)	Comment
Default case (EG3.2.xls)	6.7 x 10^{-8}	2.9 x 10^{-9}	33	Acceptable risk
Remove geomembrane (EG3.2a.xls)	3.8 x 10^{-13}	4 x 10^{-6}	15	Increased volumes of leachate generated. Acceptable risk
** default conditions apply unless stated* *Note: The number of significant figures reported is for illustration and not because there is such a high level of confidence in the results.*				

The spreadsheet predicts that for ammonium, both designs for the landfill are acceptable, although the risk is lower without a geomembrane present, however this situation would result in increased volumes of leachate being generated.