GasSim: Landfill Gas Risk Assessment Model

G. M. Attenborough*, D. H. Hall**, R. G. Gregory[o], and L. McGoochan[+]

* Golder Associates (UK) Ltd, Maidenhead, Berkshire, SL6 8BY, UK
** Golder Associates (UK) Ltd, Nottingham, NG12 4DG, UK
[o] Land Quality Management Ltd, Nottingham, NG7 2RD, UK
\+ Environment Agency, Orchard House, Endeavour Park, London Road, Addington, West Malling, Kent, ME19 5SH

SUMMARY: The emissions of bulk and trace gases from landfills created either directly from waste decomposition or from the combustion of landfill gas (LFG) during flaring and/or gas utilisation, have the potential to impact the global atmosphere, the local environment and expose humans to potential health risks. GasSim assesses the likelihood of these processes and the magnitude of the impacts and considers the uncertainty in processes and parameters, using a Monte Carlo Simulation, in a reproducible manner.

1. INTRODUCTION

There have been two principal drivers behind the development of GasSim. First was the need to substantiate the potential health effects of living near and working on landfills. UK and European research (Elliott et al, 2001; Vrijheid et al, 2002) have both indicated a statistical (but not necessarily causal) relationship between an adverse effect on human health, e.g. birth defects, and landfill emissions. Second was the need for a management tool to help the UK meet the Kyoto requirement to reduce the emissions of greenhouse gases to the environment. Methane is the second most important anthropogenic greenhouse gas, after carbon dioxide, and is emitted from landfills in significant quantities.

There are three European Union (EU) Directives, which apply to the generation and management of landfill gas:

- the European Union Waste Framework Directive (EC, 1991) requires that waste is recovered or disposed without using methods that could endanger human health or harm the environment;
- the Landfill Directive (EC, 1999) requires waste operators to control the accumulation and migration of LFG, to collect and flare or utilise LFG from landfills receiving biodegradable waste, and minimise damage or deterioration of the environment;
- the Integrated Pollution Prevention and Control (IPPC) Directive (EC, 1996) requires preventative measures are taken against pollution through flaring and utilisation.

These directives, which are being implemented into UK regulations, cover the design, construction, operation and maintenance of the landfill gas management systems and require:

- gas management systems to control the migration and release of landfill gas;
- minimising the contribution to global warming;
- management of odour; and
- reporting of releases of named pollutants (the Pollution Inventory). This will require monitoring of gas generation, surface emissions, and combustion plant emissions, including tracking and reporting the changes to these emissions through time.

Therefore it has become policy in the UK that gaseous emissions from permitted landfill sites will be regulated according to site-specific risk management practice to minimise the impact on:
- health from trace components and combustion products;
- the local environment by odour and vegetation stress; and
- global atmosphere by ozone depletion and global warming.

The risk of these processes occurring is normally assessed using a mixture of experience, calculations and computer models. GasSim has therefore been developed to support the risk assessors' experience by providing a standard methodology and landfill gas management tool for the Environment Agency, operators and consultants. In order to quantitatively evaluate the risks of these processes and the magnitude of the impacts, GasSim considers the uncertainty in input parameters using a Monte Carlo Simulation. Allowing Parameter uncertainty (and to some extent model uncertainty) to be dealt by specifying a range of values for each input parameter rather than a single number, using probability density functions (PDFs). GasSim is designed to aid LFG risk assessment, by enabling LFG generation, emissions, migration/dispersion and impact/exposure to be assessed in a reproducible manner by those familiar with the subject.

GasSim has been developed from the HELGA framework (Gregory et al., 1999), which was also developed for the Environment Agency.

2. CONCEPTUAL MODEL

The conceptual model (Figure 1) has a modular structure. Each module incorporates the effects of additional processes. Progression to successive modules is only necessary if this information is required, e.g. LFG generation and emissions can be determined without proceeding through subsequent modules to optimise time and data collection constraints.

GasSim is divided into 5 main modules (or assessment stages), described in detail below:
- source term gas generation;
- gas emissions;
- environmental transport through atmospheric dispersion;
- environmental transport through terrestrial lateral migration; and
- exposure and environmental impacts.

2.1 Source

2.1.1 Bulk gases

The heart of the model is the source term, which simulates the generation of methane, carbon dioxide, hydrogen, and hydrogen sulphide produced from the following waste characteristics:
- the waste breakdown, the mix of different waste streams e.g. domestic, civic amenity and commercial waste;

- the waste composition, the fractionation or make-up of the waste e.g. the proportion of paper, textiles and putrescible materials. The waste fractions are defined by the percentage of the material that can decompose, the proportion of cellulose and hemi-cellulose, and the moisture content of the fraction;
- the waste moisture content, from the infiltration, leachate management, and waste physical parameters; and
- the biodegradability of the waste fractions, the rate of decay of cellulose in the waste fractions.

The definition of these input parameters allows the model to be highly flexible and tailored to individual landfill sites, taking account of specific waste streams, filling/deposition rates and environmental conditions.

The methanogenic degradation of carbon is either simulated by dividing the waste make-up of the different waste streams into three waste fractions, which degrade slowly (newspaper), moderately (Miscellaneous combustible) and rapidly (putrescibles). Alternatively this can be determined using the LandGem equation (Pelt *et al.*, 1998). These equations both determine quantity of available carbon, which is used to determine the generation of methane and carbon dioxide, using the methane to carbon dioxide ratio.

2.1.2 Trace Gases

The generation of trace gases is simulated by the user defining the concentration of the trace gas or selecting a typical value (mg/m^3) within the bulk landfill gas. GasSim determines the quantity of trace gas generated by proportioning the concentration of the trace gas species to the LFG generation rate. Additionally GasSim allows the option to reduce the trace gas concentration over time, using a half-life decay declining source term.

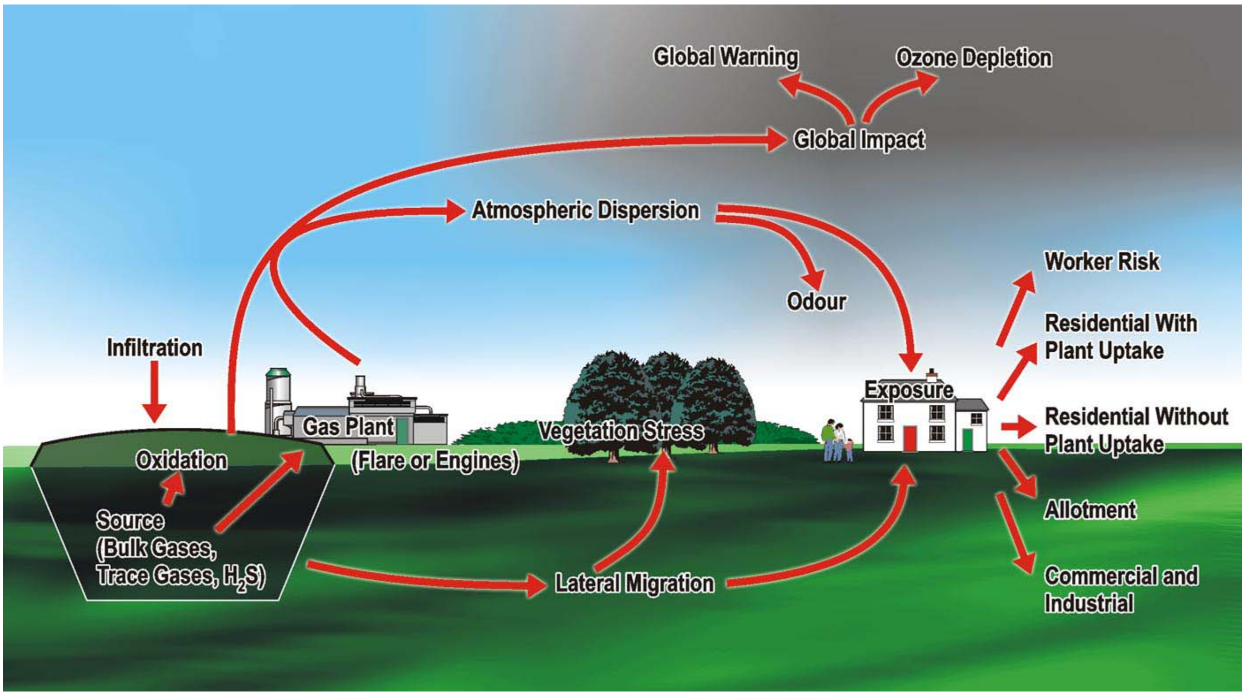

Figure 1. The GasSim Conceptual Model

2.2 Emissions

Emissions from a landfill are normally, but not always, controlled by engineering measures, e.g. the installation of engineered barriers (cap and liner) and gas collection system. The gas collected can then be flared or utilised. The model assumes that any LFG generated and not collected will be emitted through the landfill cap or liner at a steady state.
The emissions from engines and/or flares are determined from the quantity of gas abstracted and the:

- concentration of the species in LFG and/or the combustion emissions;
- concentration of a parent species, which reacts to form the emitted species, in LFG; or
- the monitored concentration of the emissions.

2.2.1 Surface and Lateral Emissions

GasSim is a steady state model that assumes that all the gas generated is emitted by some pathway or another. This gas will be collected and used by flares and/or engines or lost uncontrollably through the surface or the lateral liner. The surface emissions are determined by a combination of the emissions for the capped and operational, uncapped area. This differentiation is made since GasSim assumes that gas generated from the uncapped area is emitted directly through the surface. without methane oxidation. It is assumed the open surface of the waste will be far more permeable that the sides of the landfill, which may or may not be engineered. The surface emissions are calculated using the percentage of the uncapped area and the gas generation. Therefore this percentage is defined as a fractional tonnage of waste in place.

For the engineered surfaces, the proportion of emissions lost laterally through the side liner, compared to the proportion lost through the capped surface is calculated and partitioned using the permeability, thickness and unsaturated surface area of the most impervious layers of each. GasSim assumes that gas movement is via plug flow and that both the cap and liner are homogenous and isotropic, even though in practice poor cap/liner construction and maintenance can result in cracks and micro-fractures. Although these may be locally important, their net effect on the emissions will be averaged out across the site. In some cases the most impervious layer could be the waste itself, which is also assumed to be homogenous and isotropic.

GasSim also allows the option to reduce the emissions of methane through the cap by biological methane oxidation by simulating the quantity of emission that pass though that cap (and are subject to oxidative processes) compared to that which passes unoxidised through fissures. The model allows the use of the IPCC methodology (IPCC 1996a, 1996b), or a user defined approach. Here, the emissions through the cap are simulated to reduce by a user defined or default percentage if more that 30 cm of soil is present above the cap, and the amount of fissuring can be specifically modelled.

GasSim simulates the surface and lateral emission of trace gases using the concentration of the species per m^3 of LFG and the LFG emission rate, by proportioning the quantity of trace gas generated along the same lines as the as the bulk gases.

2.3 Environmental Transport

Contaminant transport laterally through the geosphere is simulated using an advection-dispersion equation. Dispersion through the atmosphere is simulated using frequencies of different wind speeds and stability categories occurring.

2.3.1 Lateral Migration

This is simulated simplistically assuming one-dimensional plug flow, which is emitted uniformly from all sites of the landfill. The module uses an advection and dispersion equation to determine the migration of gas emitted through the landfill liner, this is similar to the equation used for the migration of contaminant in groundwater by LandSim II (Environment Agency, 2002). The advection term is determined by the pressure in the landfill, which is proportional to the quantity of gas that migrates laterally. GasSim assumes that the landfill is at steady state, therefore the velocity at which the gas escapes the landfill can be determined. The dispersion term simulates the concentration gradient, using the dispersivity of the gas in air with corrections for the soil porosity and moisture content.

2.3.2 Atmospheric Dispersion

Atmospheric dispersion of the emissions from the engines, flares and the surface is simulated using the NRPB R91 gaussian plume model (NRPB, 1995). This takes into account the effects of thermal plume rise associated with flares and engines and simulates the removal of gases form the atmosphere by both wet and dry deposition. GasSim assumes that the emissions from the landfill represent a point source.

The module simulates the dispersion of the gases using meteorological data, e.g. the wind rose, the frequency of different Pasquill stability conditions, and the average wind speeds and mixing layer heights for each of the stability conditions.

2.4 Impact/Exposure

The impact of the emissions can be assessed in four different ways, by determining the:

- global warming and ozone depletion potential (GWP and ODP);
- vegetation stress at a given distance;
- distance from the landfill of the odour threshold; and
- on-site worker, and off-site indoor and outdoor exposure.

2.4.1 Climate change

The contribution that the landfill has on climate change is determined by calculating the GWP and ODP, of the emissions from engines, flares and through the surface. The emissions through the lateral liner are not included as this is an unintentional release pathway.

2.4.2 Vegetation stress

The impact of methane and carbon dioxide emitted from the landfill on the vegetation in the local environment can also be simulated. This is undertaken by determining the point at which the laterally migrated gases reduces below a default or user defined level above which vegetation stress is known to occur.

2.4.3 Odour

The impact of odour is assessed in two ways, the first determines the point at which the concentrations of odorous species fall below the Odour Threshold Value. This is simulated using the atmospheric distribution of the odorous species. The second method simulates the emissions of European Odour Units from the uncapped, capped and discrete features e.g. passive venting wells and fissures.

2.4.4 Exposure

Exposure to humans is determined for a number of set scenarios:

- Residential with plant uptake;
- Residential without plant uptake;
- Allotments;
- Commercial & Industrial; and
- Worker exposure.

Each of these exposure scenarios has a set number of exposure pathways and a default set of exposure factors based on a member of the critical group, and each contaminant considered has a contaminant specific set of physico-chemical properties associated with it.

GasSim primarily undertakes this exposure assessment following the approach used in the CLEA model (Environment Agency and DEFRA, 2002), with some minor modifications.

3. DATA INPUTS AND MODEL VERIFICATION

The model verification has included comparing the GasSim multi-phase equation with equations from the HELGA framework and LandGem, using the scenario receiving 500,000, 700,000, 800,000, 800,000, and 500,000 t respectively for 5 years. GasSim was first compared to HELGA using the three decay rates: fast - 0.044 (6 years); medium - 0.076 (9 years); and slow - 0.116 (15 years). The methane to carbon dioxide ratio was set at 50:50 and the simulation carried out using a domestic waste stream. This scenario was also compared to LandGem, using a methane generation rate of 0.077 (9 years) and a typical UK cumulative methane generation capacity of ~64 m^3/t.

The comparison of the models using the cumulative gas yield per tonne during the 150 years simulation has been tabulated in Table 1. The GasSim model compares very well to spreadsheet calculations using the HELGA framework (within 0.5%) and to LandGem (4%).

Additionally the single phase equation in GasSim has been compared to LandGem for the same scenario using the LandGem CAA and AP42 default inputs, using total gas generated per tonne during the 150 years simulation (Table 2). The models agree within 2.6%.

4. MODEL VALIDATION

In order for any model to be used with confidence, it is essential that its represents reality. Therefore a series of validation trials have been undertaken, a selection of which are included.

Table 1. Verification - UK Scenario

Model	**CH_4 (m^3/t)**	**CO_2 (m^3/t)**	**Total LFG (m^3/t)**
GasSim	63.7	63.7	127.5
LandGem	66.3	66.3	132.5
HELGA	63.8	63.8	127.6

Table 2. Verification – AP42 and CAA Default Scenarios

Model	**CH_4 (m^3/t)**	**CO_2 (m^3/t)**	**LFG (m^3/t)**
LandGem AP42	99.6	99.6	199.3
GasSim AP42	101.7	101.7	203.5
LandGem CAA	169.7	169.7	339.5
GasSim CAA	174.2	174,2	348.4

4.1 Validation of LFG Generation against Test Cells

The bulk gas source generation term has been validated against the LFG production data collected by the University of Strathclyde from the Auchencarroch Test cells. The cells had received a range of treatments and therefore the sum of all the emplaced waste for the gas produced 2 and 3 years after filling has been used to validate the model.

4.2 Validation of LFG Generation and Surface Emissions against UK Landfill A

The bulk gas source generation and surface emissions modules have also been validated against a landfill in the UK (Landfill A), which has received 2 million tonnes of domestic waste over an eight year period, receiving 200,000 t/y for the first four years, 260,000 t/y for the next two years and 333,000 t/y for the final two years. The simulated data were compared to monitoring data obtained 18 to 20 years after filling commenced.

The landfill was constructed with a 1m CQA clay cap and liner, compacted to a specification of $1x10^{-9}$ m/s, and occupies an area of 7 ha. The site contained gas plant that could abstract between 700 and 1000 m^3/hr, which was simulated at two different collection efficiencies:

- Scenario 1: 85% LFG collection efficiency and 70% biological oxidation of fugitive methane in the cap:
- Scenario 2: 85% LFG collection efficiency and 90% biological oxidation of fugitive methane in the cap:

4.3 Validating the Surface Emissions against UK Landfill B

The bulk gas source generation module has also been validated against a second UK landfill (Landfill B), which has received 1.6 million tonnes of predominantly commercial waste, with varying quantities of domestic and inert material, over a 24 year period. The carbon dioxide to methane ratio of 43%: 57% was determined by on-site monitoring. The landfill occupies an area of approximately 24 ha.

The 0.65m landfill clay cap was completed in 2002. The liner was constructed to 1.5m thick, with both the cap and the liner engineered to a CQA specification of $1x10^{-9}$ m/s.

The site contained one 450 m^3/hr engine and four flares (three 50-500 m^3/hr and one 100-1500 m^3/hr), which were assumed to be operating at 90% efficiency.

4.4 Validating the Trace Gas Surface Emissions against Green Valley Landfill (USA)

The trace surface emissions module has been validated against Green Valley landfill site (USA), which has been monitored for the emissions of a number of trace gas species (Bogner et al., 1997). GasSim has been validated against the emission rates for benzene, tetrachloroethene, trichloroethene and vinyl chloride using default inputs and a half life of 4.11 ± 1.56 years.

The landfill has been simulated as receiving 146,454.5 t/y for 22 years, with a compacted clay cap, with a surface area of 8 ha site. The site contained two 2345 m^3/hr engines and two 3541 m^3/hr flares, which were assumed to be operating at between 70 and 90% efficiency.

4.5 Validation Outcomes

The monitored gas productions for both validations have been overlain on the simulated gas production curve (Figure 2 and 3) indicating that the simulated LFG production is within or very close to the range of monitored results.

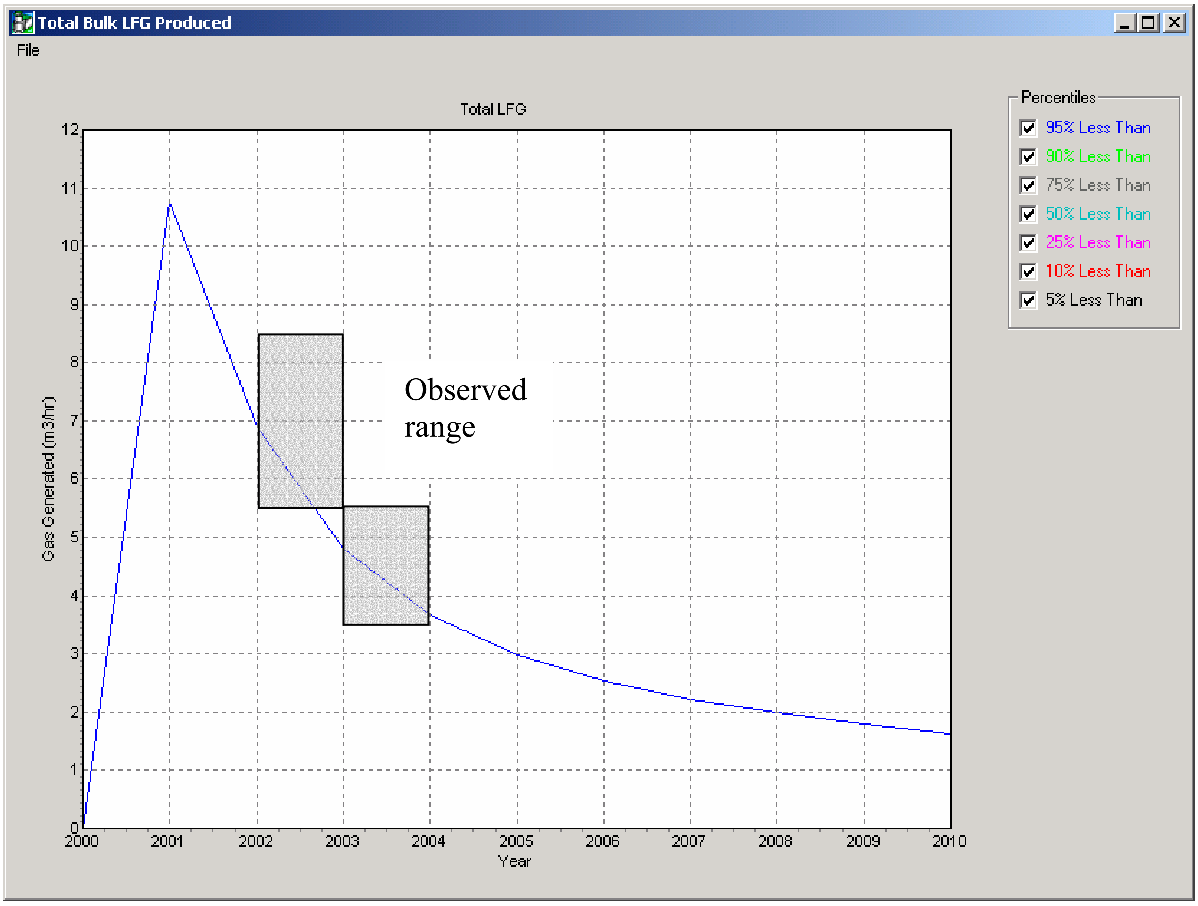

Figure 2. Auchencarroch Test Cells: Modelled Data Overlain By Observed Range

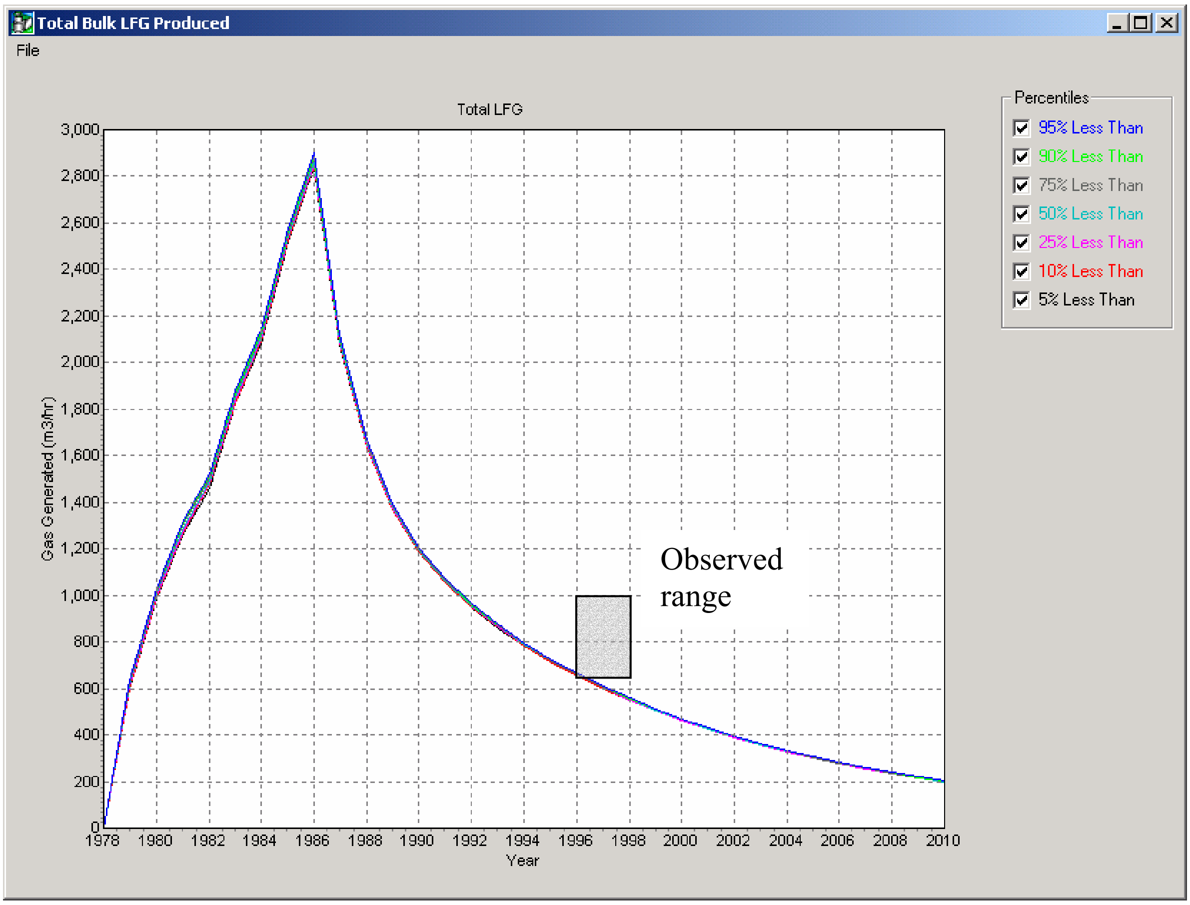

Figure 3 UK Landfill: Modelled Data Overlain By The Observed Range

Table 3 Green Valley simulated and observed trace gas emissions.

Species	GasSim Outcome		Bogner et al. (1997) Reported range	
	5% ($mg.m^{-2}s^{-1}$)	95% ($mg.m^{-2}s^{-1}$)	Min ($mg.m^{-2}s^{-1}$)	Max ($mg.m^{-2}s^{-1}$)
Benzene	$8.9x10^{-6}$	$1.3\ x10^{-2}$	-	$5.37\ x10^{-5}$
Tetrachloroethene	$6.3\ x10^{-6}$	$1.6\ x10^{-1}$	$3.99x10^{-7}$	$1.23\ x10^{-5}$
Trichloroethene	$3.6\ x10^{-5}$	$5.1\ x10^{-2}$	$4.50\ x10^{-10}$	$3.10\ x10^{-6}$
Vinyl Chloride	$1.6\ x10^{-5}$	$1.8\ x10^{-2}$	$9.61\ x10^{-6}$	$3.18\ x10^{-5}$

The bulk LFG surface emissions module predicts that the average net surface emissions after allowing for LFG collection and biological methane oxidation for UK landfill A lies between 10^{-1} $mg.m^2s^{-1}$ and 10^{-3} $mg.m^2s^{-1}$, for both scenarios. The values are slightly higher than those reported in the HELGA framework, which is a reflection of the incorporation of the landfill surface area into the equation determining the average net surface emissions. However, these values are within the range observed for similar sites reported in the HELGA framework (10^{-4} – 1 $mg.m^2.s^{-1}$) depending on the methodology used to determine the emissions, (Gregory *et al*. 1999).

The Landfill B simulation predicts that the average net surface emissions after allowing for LFG collection and biological methane oxidation are between $2x10^{-2}$ and $5x10^{-2}$ $mg.m^2s^{-1}$. These values were within the range of methane emissions reported in the field from the different capping types, which ranged from $2x10^{-4}$ $mg.m^2s^{-1}$ to $4x10^{+2}$ $mg.m^2s^{-1}$, and were very close to the net average emission of $9x10^{-2}$ $mg.m^2s^{-1}$

The trace gas validation for Green Valley landfill indicated that the observed range of benzene, tetrachloroethene and vinyl chloride were in the range that GasSim predicts (Table 3). GasSim over estimates the emissions of VOCs with the 5 percentile GasSim emissions occurring at a similar order of magnitude as the maximum observed emission. This is due to GasSim not simulating the reduction of VOCs in the soil cap by micro biological and other processes, as discussed by Bogner *et al.,* (1997) and the limited observed data not detecting high emissions sources, e.g. fissures.

5. CONCLUSIONS VALIDATING THE MODEL

The GasSim model was designed to allow the risks for LFG to be assessed during both at the planning, operational and post operational stages of a landfill stages to aid decision making, to minimise the impact on local receptors, by allowing the simulation of different capping designs and flare/engine combinations. This assessment includes a quantitative assessment of the risks to humans, vegetation, the atmosphere, and the extent of odour releases.

The landfill can be simulated using a limited amount of site-specific data, with uncertainties in the data sets modelled using PDFs and Monte Carlo simulation. Generic data is provided, which covers information that operators are unlikely to have, e.g. for trace gas concentrations, destruction efficiencies of flares and composition of different waste streams.

The verification trails have demonstrated that the GasSim model produces results that agree with other models, namely LandGem and the equations used in HELGA framework. The initial validation trails are encouraging with the source and emissions modules simulating gas production in accordance with reality. The lateral migration, atmospheric dispersion, and human offsite exposure modules are (at the time of writing) currently undergoing verification and validation.

6. ACKNOWLEDGEMENTS AND DISCLAIMER

The Environment Agency of England and Wales (the Environment Agency) has funded the development of the model to allow risk assessment for LFG impacting receptors at the planning stage and at the operational stage to aid decision making. The views expressed in this paper are those of the authors and are not necessarily those of the Environment Agency.

7. REFERENCES

Bognor, J., Spokas, K., Niemann, M., Neimann, L., and Baker, J., (1997) Emissions of non-methane organic compounds at the Illinois (USA) landfill site: preliminary field measurements, Sardinia 97, Sixth International Landfill Symposium, S. Margherita di Pula, Cagliari, Italy. pp 127 – 138. CISA, Cagliari, Italy.

EC, 1991, "Council Directive 75/442/EEC on waste, as amended by Council Directive 91/156/EEC concerning The Framework Directive on Waste". Official Journal of the European Communities.

EC, 1996. "Council Directive 96/61/EC of 24 September 1996 concerning Integrated Pollution Prevention and Control". Official Journal of the European Communities.

EC, 1999. "Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste". Official Journal of the European Communities.

Elliott, P., Morris, S., Briggs, D., de Hoogh, C., Hurt, C., Jensen, T. K., Maitland, I., Lewin, A., Richardson, S, Wakefield, J., and Jarup, L., 2001. "Birth outcomes and selected cancers in populations living near landfill sites". Report to the Department of Health by the Small Area Health Statistics Unit (SAHSU), Department of Epidemiology and Public Health, Imperial College, London.

Gregory, R. G., Revans, A. J., Hill, M. D., Meadows, M. P., Paul, L. and Ferguson, C. C., 1999, "A framework to assess the risks to human health and the environment from landfill gas", Environment Agency Technical Report P271, under contract CWM 168/98.

Environment Agency, 2002, "LandSim, Landfill Performance Simulation by Monte Carlo Simulation", Environment Agency R&D Publication 120.

Environment Agency and DEFRA, 2002, "The contaminated land exposure assessment model (CLEA): Technical basis and algorithms2", Document prepared by the National Groundwater and Contaminated Land Centre of the Environment Agency R&D Publication CLR10.

Intergovernmental Panel on Climate Change, 1996a. "Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual, Chapter 6".

Intergovernmental Panel on Climate Change, 1996b. "IPCC Expert Group on Waste, Topical Workshop on Carbon Conversion and Methane Oxidation in Solid Waste Disposal Sites", Argonne National Laboratory, Chicago, USA, 25 October 1996.

NRPB, 1995. "Methodology for assessing the radiological consequences of routine releases of radionuclides to the environment", Report EUR 15760, Luxembourg, European Commission.

Pelt R., White C., Blackard A., Bass R. L., and Burklin C., and Heaton R. E., 1998, "User's Manual Landfill Gas Emissions Model", U.S. Environmental Protection Agency Contract 68-D1-0117, EPA.

Vrijheid M., Dolk H., Armstrong B., Abramsky L., Bianchi F., Fazarinc I., Garne E., Ide R., Nelen V., Robert E., Scott J. E. S., Stone D. and Tenconi R. (2002). Chromosomal congenital anomalies and residence near hazardous waste landfill sites. The Lancet, 359, 320-322.