Elsevier Editorial System(tm) for Waste Management
Manuscript Draft

Manuscript Number:

Title: COMPARISON OF DIFFERENT APPROACHES FOR THE ESTIMATION OF ODOUR EMISSIONS FROM LANDFILL SURFACES

Article Type: SI:Sanitary Landfilling

Keywords: odour impact assessment; dispersion modelling; surface sampling; wind tunnel; satatic hood; flux chamber.

Corresponding Author: Dr. Laura Capelli, Ph.D.

Corresponding Author's Institution: Politecnico di Milano

First Author: Federico Lucernoni

Order of Authors: Federico Lucernoni; Laura Capelli; Selena Sironi

Abstract: The study addresses the problem of the assessment of odour emissions from landfills. The aim of the project is the research concerning how to quantify odour emissions from landfill surfaces, since there is no evidence of a widely accepted method to evaluate odour emissions from this particular kind of source. Seven different methods have been developed and investigated; these methods can be seen as based on three distinct approaches to the problem, both experimental and computational. The first approach provides to use models for the estimation the landfill gas production, whereby the second and the third approach are based on direct measurement campaigns on the landfill surface, for the determination either of the methane or for the direct measurement of the odour concentration. The methods have then been compared in terms of resulting odour impact by application of a specific atmospheric dispersion model.

Suggested Reviewers: Günther Schauberger
gunther.schauberger@vetmeduni.ac.at
Prof. G. Schauberger has worked in this field and he might be interested in reviewing the paper I am submitting.

Enrico Davoli
enrico.davoli@marionegri.it
E. Davoli has worked in this field and he might be interested in reviewing the paper I am submitting.

Martin Piringer
martin.piringer@zamg.ac.at
M. Piringer has worked in this field and he might be interested in reviewing the paper I am submitting.

Dipartimento di Chimica, Materiali e Ingegneria Chimica
“Giulio Natta”
Laboratorio Olfattometrico
Politecnico di Milano

tel. 02-2399.3206
fax.02-2399.3291
e-mail: labolfattometrico@chem.polimi.it

Piazza Leonardo Da Vinci, 32 – 20133 MILANO

Comparison of different approaches for the estimation of odour emissions from landfill surfaces

Lucernoni, L. Capelli, S. Sironi

The present work addresses the issue of assessment of odour emissions from landfills, an aspect that in recent years has become a very important matter, for researchers and managers as well as for the general public. The aim is to shed some light on the quantification of odour emissions from landfill surfaces, since there is no evidence of a widely accepted methodology. The methods that are here presented can be seen as based on three distinct approaches to the problem, both experimental and computational. The first approach entails the use of specific models for the estimation the landfill gas production, whereby the second and the third approach are based on direct measurement campaigns on the landfill surface, for the determination either of the methane or of the odour concentration. The methods have then been compared in terms of resulting odour impact by application of a specific atmospheric dispersion model.

As novelty of this work and its contributions to the field of olfactometry and odour dispersion modelling, please consider our paper “Comparison of different approaches for the estimation of odour emissions from landfill surfaces” for publication on Waste Management Journal.

The paper was presented during the Sardinia Symposium 2015 and resulted a selected paper considered for publication on Waste Management Journal.

We hope this paper will be of interest for the readers of this journal.

Best regards,

Laura Capelli and Federico Lucernoni

COMPARISON OF DIFFERENT APPROACHES FOR THE ESTIMATION OF ODOUR EMISSIONS FROM LANDFILL SURFACES

F. LUCERNONI, L. CAPELLI*, S. SIRONI

Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering "Giulio Natta" - Piazza L. da Vinci 32, 20133 Milano, Italy

** laura.capelli@polimi.it*

ABSTRACT: The study addresses the problem of the assessment of odour emissions from landfills. The aim of the project is the research concerning how to quantify odour emissions from landfill surfaces, since there is no evidence of a widely accepted method to evaluate odour emissions from this particular kind of source. Seven different methods have been developed and investigated; these methods can be seen as based on three distinct approaches to the problem, both experimental and computational. The first approach provides to use models for the estimation the landfill gas production, whereby the second and the third approach are based on direct measurement campaigns on the landfill surface, for the determination either of the methane or for the direct measurement of the odour concentration. The methods have then been compared in terms of resulting odour impact by application of a specific atmospheric dispersion model.

Keywords: odour impact assessment; dispersion modelling; surface sampling; wind tunnel; satatic hood; flux chamber[1].

LFG: landfill gas
OER: Odour Emission Rate
SOER: Specific Odour Emission Rate

1. INTRODUCTION

Olfactory pollution is the immission of polluting compounds in the atmosphere that, although if not directly dangerous for the human health, are nonetheless characterized by intense and/or unpleasant smell. Typical examples are gaseous emissions coming from landfill surfaces (Ying et al., 2012), intensive farming, etc. This kind of pollution is one of the most significant causes of environmental discomfort since it lowers the quality of the environment and it may lead to psychophysiological disorders and a general worsened life quality (Palmiotto et al., 2014). In Italy there are no comprehensive regulations concerning the problem of odoriferous emissions. In order to devise proper strategies to reduce the nuisance related to odour emissions it is necessary to have specific methods for univocal odour assessment (Balling et al., 1980; Hobson, 1995; Stordeur, 1981), debunking the common belief that odour characterization is more art than science (Koe, 1989; Jiang, 1996). While in the scientific community there is a satisfactory agreement regarding the analytical techniques – i.e. dynamic olfactometry for the determination of odour concentration (Sironi et al., 2014) – odour sampling is a quite more debated task, especially if diffused emissions or area sources are concerned. The evaluation of odour emissions from landfills is even more complicated, due to the specific characteristics of this kind of source, which is surely not an active area source, but neither properly a passive area source, as the landfill surface is typically crossed by a – low – flux, and there is currently no widely accepted method for odour assessment on landfills. However, landfills have always been considered as important sources of unpleasant odours, for this reason the development of specific methods for the assessment of odours emissions or the definition of specific odour emission factors would be of great interest both for environmental authorities, as well as for landfill managers and operators.

This is the reason why, in the present work, different methods for the evaluation of odour emissions from landfills have been inspected: the 7 methods developed are all retraceable to one of three distinct approaches to the matter.

The first approach – that comprises methods 1 and 2 - entails the usage of specific software for the quantification of the landfill gas (LFG) production: the software used in the first method is the US-EPA LandGEM, while the second method exploited a similar software specifically developed for the present project with some improved features with respect to the US-EPA LandGEM.

The second approach – that includes the third method – relies on the direct measurement of CH_4 on the landfill surface, which involved the necessity to define a sampling methodology tailored for this peculiar type of source.

The third approach – that comprises methods 4, 5, 6 and 7 – involves the direct measurement of the odour concentration at the source. In the fourth method the concentration was considered independent from the wind speed, while in methods 5, 6, 7 the landfill surface was treated as a liquid area source, thereby considering the concentration as a function of the wind speed on the surface (Sironi et al., 2005).

Since the first two approaches evaluated are based on the quantification of methane emissions, the Odour Emission Rate (OER) needs to be obtained indirectly by multiplying the emitted gas flow rate by the LFG odour concentration. The odour concentration (c_{od}) of the LFG emitted through the landfill surface was estimeated by means of a correlation investigated between c_{od} and c_{CH_4}.

The OER values obtained with the seven descripted methods were then used as inputs to run the atmospheric dispersion model CALPUFF, which allowed to visualize the odour impacts of the studied landfill resulting from the different emission scenarios considered. The impacts have then been compared with one another in order to make some consideration about the different models' accuracy and reliability.

2. MATERIALS AND METHODS

2.1 The Studied Site

The chosen landfill is located in Northern Italy, and it is classified as “Landfill for Non-Hazardous Municipal Solid Waste Disposal”.

The site was chosen because it is object of repeated olfactometric monitoring campaigns by the Olfactometric Laboratory of Politecnico di Milano since several years: this allows to have access to a great amount of emission, olfactometric and meteorological data, as well as a consolidated experience about the landfill odour impact gained throughout the years, both crucial aspects for the present work. The landfill is operational since the early 1990s and has a waste processing capacity of several millions cubic meters, making it one of the biggest landfills in Northern Italy. The site is subdivided in six allotments: now only one allotment is still active, all the others are closed.

In order to be able to apply the dispersion model to the emissions coming from a landfill, the whole area (about 250’000 m^2) needs to be considered as an emission source. For modelling purposes the landfill surface was divided in a reasonable number of emissive cells having smaller dimensions: 40 emissive cells were considered, a number of sources that is in line also with the suggestions of the User’s Manual of the CALPUFF software (Scire et al., 2000). The geometry of the cells was kept as simple as possible (simple shapes like squares and triangles).

In order to glean the emission scenarios relying on an experimental approach it was also necessary to carry out tailored campaigns in the field. The campaigns spanned from 1/3/2014 to 30/10/2014 and interested mainly allotment 1, which is the oldest one.

The software initially used to assess the methane production is the US-EPA LandGEM (Alexander et al., 2005); hereafter another newer software was adopted, similar to the default LandGEM but with some reasoned modifications. This will be discussed in the following sections.

2.2 Modifications To The LandGEM Software

One of the novel aspects of the present study regarded the modification and improvement of the US-EPA LandGEM software aiming to optimize its performances. The main improvement concerns the input mode of the initial parameters of the model which the software is very sensitive to. More in detail, the biggest flaw in the default model is in the input procedure of the fundamental parameters of the model, since besides the waste inflow that can be considered changing year by year, the other parameters, i.e. the methane generation rate (k) and the methane generation potential (L_0), are kept constant for the whole simulation (Alexander et al., 2005). This aspect makes it impossible to account for the possible variations that may occur as a consequence of a change in the processed MSW quality, given that both (k) and (L_0) show a strong dependence on the bio-degradability of the considered waste.

The many regulations addressing the problem of landfill management have defined the "classes" of wastes treated there and this classification has been known to change over time. In the end it is the class of the waste that affects the most the two input parameters (k) and (L_0): at this point it is evident that assuming them unchangeable is an unacceptable approximation. Thus, the innovative idea is the possibility of considering these two key parameters as well varying year by year. The modified software maintains the same Graphical User Interface (GUI) in MS Excel as the standard US-EPA LandGEM and allows to consider the parameters (k) and (L_0) changing yearly.

2.3 Design And Development Of Specific Sampling Procedures

It is necessary to clarify the particular nature of the landfill source typology. This kind of source is an area source but it cannot be defined neither active nor passive, referring to the classification made in the german guideline VDI 3880 (VDI, 2011). In fact, even if not presenting a significant outflow – typical of the active sources – it has a distinct non-zero emission flow that cannot be neglected. This is why it is necessary to develop specific sampling devices and procedures for this unique type of source.

The first method adopted for the direct measure of methane emissions on the considered landfill surface was the so-called Static Hood device (SH) that was specifically realized starting from a design found in the scientific literature that was deemed appropriate (Rachor et al., 2013). The mentioned work was picked as reference since it is a rare example of a study that involved tests and experiments in the field that were repeatable and that were performed over a rather long period (i.e. 2 years). The hood geometry proposed in that research paper is cylindrical, 50 cm high with a base section of 0.12 m^2. Within the research group further considerations were pondered concerning the geometry of the hood. In particular, about the height of the chamber two considerations were made, concerning on one hand molecular diffusion, the most significant phenomenon in the process, and on the other hand the CH_4 ascension velocity, which depends on the LFG outflow from the landfill surface, and was hypothesized as monodimensional (perpendicular to the surface).

Since both processes are rather slow, it was concluded that it was necessary to have a shorter hood, minimizing its height in order to have a homogeneous methane concentration profile in the hood. The chamber assembled at Politecnico is 10 cm high, allowing both an easy placement of the hood on the surface and an accurate measure; the base section is 0.25 m^2 and the material used is steel, providing the required robustness to withstand the stresses involved in the laying of the device. The chamber is provided with lateral flanges to avoid excessive plunging in the soil. The hood is equipped with an open tube that connects the interior to the exterior of the hood, in order to keep the internal pressure equal to the external pressure, thus avoiding overpressures that may affect the LFG emission from the surface portion covered by the hood.

The emitted methane flow can be evaluated according to the following mass balance:

$$Q_{CH_4} = \frac{V_{hood}}{S_{hood}} * \frac{\partial c_{CH_4}}{\partial t} \quad (1)$$

Once the CH_4 flow rate is known, it is possible to calculate the LFG emission by considering the LFG composition (i.e., the CH_4 content). A specific procedure for sampling was designed, providing that after each measurement the hood is lifted and ventilated, in order to minimize LFG build-up in the hood and perturbations on the emission source. Afterwards, the hood is positioned on the same spot and the next measure is performed, restarting the time count from time zero.

After the found experimental correlation was proved to agree with the theoretical expectations, the sampling time for measurements with the static hood was defined in 10 minutes. The hood developed is portrayed in Fig.1.

Figure 1

Another device was involved in the study, a Flux Chamber (FC) similar to the one designed by the US EPA (Klenbusch, 1986) to be used in fluxed experiments. The hood realized at Politecnico is hemispherical with a 50 cm diameter and a 32 dm^3 volume. The emitted methane flow in this case can be calculated as shown in Eq.2 where the fluxes are expressed in dm^3/h:

$$F_{air} + F_{CH_4} = F_{out} \quad (2)$$

This sampling procedure is the one used for collecting samples to be analysed by means of olfactometry. The main reason behind is that odour samples have typical volumes of 6 dm^3 and considering a static hood with a volume of 25 dm^3 this would mean a huge perturbation of the system that would affect the results; the inconvenience can be overcome operating with a Flux Chamber where the volume inside the hood is constantly recirculated thanks to the continuous air flow. Also in this case different tests were performed: several experiments were conducted adopting an air flow rate ranging between 100 dm^3/h and 300 dm^3/h, thereby verifying that the measured concentration is inversely proportional to the flow rate. Then, a specific sampling procedure for the measurement of both (c_{od}) and (c_{CH_4}) with the Flux Chamber was defined. The neutral air flow rate was defined in 200 dm^3/h while the sampling time in 12 minutes. The Flux Chamber is depicted in Fig.2:

Figure 2.

Another device that was used in the present work was the Wind Tunnel (WT), which was designed at Politecnico in a previous project for odour sampling from passive area source (Capelli et al., 2009), with the aim of making the flow fluxed in the hood as uniform as possible, in order to realistically simulate the action of the wind on the surface (Jiang et al., 1995). Even if this sampling system was validated and codified only for liquid area sources – while the studies to validate it also for solid area sources are still ongoing (Capelli et al., 2012) – it was decided to use it for the determination of the odour emissions from the landfill surface since it represents the only sampling system available that has been validated for passive area sources. However, it is known that for area sources characterized by a very low emissivity, it tends to overestimate the actual emission (Frechen et al., 2004; VDI, 2011). Previous studies on the Wind Tunnel led to the definition of the optimal sweep air flow rate, found to be 2500 dm^3/h (Capelli et al., 2009). At the outlet of the Wind Tunnel an odour sample is collected in a specific Nalophan™ bag by means of a vacuum pump. From the odour concentration it is possible to evaluate the Specific Odour Emission Rate (SOER) expressed in [$ou_E/s/m^2$] according to Eq.3:

$$SOER = \frac{c_{od} * Q_{air}}{A_{WT}} \quad (3)$$

With: c_{od}= odour concentration [ou_E/m^3]

Q_{air}= sweep air flow rate [m^3/s]

A_{WT}= base section of the WT [m^2]

The OER is then obtained by multiplying the SOER by the site surface. The outlet odour concentration, the SOER and the OER, i.e. the amount of odorous compounds that migrate to the gas phase as a consequence of forced convection, are a function of the defined sweep flow rate. More in detail, considering the motion regime laminar, assuming that the mass transfer phenomena can be described by the laws of Prandtl's Fluid-Dynamic Boundary Layer Theory, it is possible to deduce that both SOER and OER will be proportional to the square root of the sweep air velocity as shown in Eq.4, where α is a proportionality constant and the hypothesis of laminar motion regime holds true:

$$SOER, OER = \alpha v^{\frac{1}{2}} \quad (4)$$

This means that the OER data obtained with the WT will need to be recalculated at the correct wind speed for each hour of the simulation time domain, before using them as inputs for the CALPUFF dispersion model (Jiang et al., 2001; Sohn et al., 2003); this operation can be done according to Eq.5:

$$OER_{v_2} = OER_{v_1} \left(\frac{v_2}{v_1}\right)^{\frac{1}{2}} \quad (5)$$

In Eq.5 v_1 is the air speed during the sampling conditions – in our case corresponding to 0.035 m/s – while v_2 is the wind speed at a specific hour of the time domain of the simulation.

2.4 Evaluation Of The Emitted LFG Odour Concentration

In order to be able to assess the odour emissions associated with the LFG emissions from the landfill surface, it is necessary to know the effluent flow rate and its odour concentration, required for OER calculation. The determination of the odour concentration of the LFG emitted from the landfill surface is a quite complicated task: in literature there are some odour concentration values relevant to pure LFG (Sironi et al., 2005), but these values overestimate the concentration of the LFG emitted through the landfill surface, as they do not consider the effects of odour concentration reduction that occur while the gas crosses the landfill surface cover material (Capanema et al., 2014). For this reason, it was decided to try to estimate the LFG odour concentration by investigating the correlation between the CH_4 concentration (in ppm) and the odour concentration (in ou_E/m^3). For this purpose, specific sampling campaigns at the landfill were conducted, where the sampling method involved the Flux Chamber both for the assessment of CH_4 concentration and for the retrieval of odour samples for olfactometric analysis. The resulting values underwent a screening process: in particular the odour concentration values below 40 ou_E/m^3 were neglected due to the detection limits that are characteristic of the olfactometric analysis. The remaining data were then plotted with methane concentration on the axis of abscissae and the odour concentration on the axis of ordinates.

The resulting correlation is here reported:

$$y = 0.6907x + 83.026 \qquad (6)$$

In Eq.6 (x) is (c_{CH_4}) in ppm while (y) is (c_{od}) in ou_E/m^3. Since in this case the CH_4 concentration in LFG is assumed to be 50%, i.e. 500000 ppm, the resulting odour concentration for the LFG turned out to be 345000 ou_E/m^3.

2.5 Optimization Of The Model For The Assessment Of The Wind Speed Depending Emission Rate

When it is necessary to recalculate OER as a function of the wind speed, it is necessary to define which wind speed has to be considered. In this sense, it was decided to investigate what differences were observed when using the wind speed recalculated at source level (at 2 m) instead of the one recorded by the meteorological station (at 10 m). Two possible laws were considered for wind speed recalculation: a Power Law and a Logarithmic Law. The resulting models and impacts were then compared with one another:

- in the first case the OER recalculation considered the wind speed recorded at 10 m;
- in the second case the OER recalculation considered the wind speed at 2 m recalculated

with a Power Law model that is obtained empirically starting from a known velocity at certain height, the height corresponding to the desired wind velocity and a so-called Hellman's parameter that depends on terrain and stability class. This can be viewed formulaically in Eq.7. The model is suggested in the heights range 30-300 m (Cook, 1997);

$$v_w^{h1} = v_w^{h2} * \left(\frac{h1}{h2}\right)^{\alpha} \quad (7)$$

- in the third case the OER recalculation considered the wind speed at 2 m evaluated with a Logarithmic Law obtained as a consequence of fluid-dynamic considerations concerning the inertial sub-layer, considering that both the "Law of the Wall" and the "Velocity Defect Law" hold true, that produces the wind profile expressed by Eq.8 (Drew et al., 2013; Tieleman, 2008):

$$v_w^h = \frac{u_*}{k}\left[ln\left(\frac{h}{z}\right) + 5.75\left(\frac{h}{H}\right) - 1.88\left(\frac{h}{H}\right)^2 - 1.33\left(\frac{h}{H}\right)^3 + 0.25\left(\frac{h}{H}\right)^4\right] \quad (8)$$

where H is the neutral boundary layer that can be calculated according to Eq.9:

$$H = \frac{u_*}{Bf} \quad (9)$$

f is the Coriolis parameter, B is an empirical constant that can be assumed equal to 6.

3. RESULTS AND DISCUSSION

3.1 Determination Of The Emitted LFG Flow Rate With LandGEM, normal and modified

It is necessary to underline that the LandGEM provides the LFG production rate, not the LFG emission, which is the quantity required for the OER calculation. First, it is necessary to input the parameters for the US EPA software. According to the regulations in force since 1993 and until 2013, the value of the production rate (k) during the landfill operation years was determined. Then the arithmetical mean of these values was picked as the value to be used in the simulations involving the standard US EPA software. The obtained value is reported in Eq.10:

$$k = 0.038\, y^{-1} \qquad (10)$$

Analogously, also for the biogas generation potential (L_0) the mean value was used for running the program; the resulting value is shown in Eq.11:

$$L_0 = 135\, m^3/Mg \qquad (11)$$

The CH_4 concentration in the LFG was considered equal to 500’000 ppm, which is the average value relvant to the site under investigation. It is possible to run the LandGEM software and obtain the flow rate of the CH_4 produced by the landfill for the year 2014, reported in Eq.12:

$$Q_{LFG} = 3.545 * 10^7\ m^3/y \qquad (12)$$

Then, knowing the LFG flow rate collected by the collection system, which in the studied case is equal to 2200 m^3/h, the LFG emission can be then evaluated as shown in Eq.13:

$$Q_{emitted} = Q_{tot} - Q_{collect} = 1872.77\ m^3/h \qquad (13)$$

The landfill OER is then calculated considering the LFG odour concentration, which was considered equal to 345’000 ou_E/m^3 (Eq. 6) as shown in Eq.14:

$$OER = Q_{emitted} * c_{od} = 179473\ ou_E/s \qquad (14)$$

It is also possible to obtain the SOER of the landfill, by dividing the OER by the surface of the site as expressed in Eq.15:

$$SOER = \frac{OER}{A_{tot}} = 0.88\ \ ou_E/(s * m^2) \qquad (15)$$

From Eq.15 it is possible to determine the OER for each emissive cell, multiplying the SOER by each cell surface. The outcome is the input for the CALPUFF dispersion model. The obtained emission data are used as input for the CALPUFF atmospheric dispersion model, producing the impact depicted in Fig.3.

The odour impact in Fig.3 is represented on a 4 km by 4 km map centred on the landfill, the shown iso-concentration lines represent the 98° percentile of the hourly averaged odour concentrations considering a peak-to-mean ratio of 2.3; this means that the mean values are multiplied by a factor that accounts for peak oscillations around the mean value of concentration over 60 minutes (Schauberger et al., 2012). The isopleths represented in the impact map refer to the range of concentration between 1 and 10 ou_E/m^3.

These parameters are a commonly accepted choice and are those suggested by the guidelines issued by Regione Lombardia (D.g.r. n. IX/3018, 2012), which is the only regulation addressing the problem of olfactory pollution available in Italy. Looking at Fig.3 it is possible to observe a significant impact since the isopleths cover almost the entire map. This result is likely to be an over-estimation of the real impact since the many years of odour monitoring campaigns conducted by the Olfactometric Laboratory of Politecnico at this exact site never highlighted a critical situation such as the one depicted in Fig.3.

Regarding the application of the modified LandGEM, considering the average rainfall of the site and the influence that the nature of the waste has on the LandGEM parameters (k) and (L_0), their values were defined for each year of landfill operation. The biogas amount produced in 2014, computed with the modified software is reported in Eq.16:

$$Q_{tot} = 3.427 * 10^7 \ \ m^3/y \quad (16)$$

Then it was possible to evaluate the actually emitted flow rate considering the same collected flow of 2200 m^3/h. Then the OER and SOER can be assessed as in the previous case. The calculations are shown in Eq.17, Eq.18 and Eq.19:

$$Q_{emitted} = Q_{tot} - Q_{collect} = 1712.58 \ \ m^3/h \quad (17)$$

$$OER = Q_{emitted} * c_{od} = 164122 \ \ ou_E/s \quad (18$$

)

$$SOER = \frac{OER}{A_{tot}} = 0.80\ ou_E/(s * m^2) \quad (19)$$

From Eq.19 it is possible to determine the OER for each emissive cell, multiplying the SOER by each cell surface. The outcome is the input for the CALPUFF dispersion model (Fig. 3, right).

Figure 3.

In Fig.3 it is possible to see the impact resulting from this method. Even if the OER is reduced with respect to the first method, the impact shown in Fig.6 is still overestimated. The new model with modified LandGEM shows an improvement since the impact over-estimation is reduced; but the main criticity relevant to this approach is that both models produce an esteem of the LFG production, not the emission and this is conceptually a step back with respect to the characterization of the LFG emissions from landfill surfaces.

3.2 Experimental Measure Of The CH_4 Concentration On The Landfill Surface

The results here presented refer to CH_4 concentration measures conducted in the field in the year 2014 adopting a sampling methodology that involved the use of a Flux Chamber with a neutral air flow rate of 200 dm^3/h. After evaluating the mean of all measured values, which turned out to be equal to 47 ppm, it was possible to determine the LFG flow rate by means of a mass balance written for the Flux Chamber. Assuming as usual that the methane concentration in the pure biogas is 50% v/v, it is possible to compute the emitted biogas flow rate as shown in Eq.20:

$$Q_{LFG} = \frac{Q_{CH_4}}{c_{CH_4}^{theo,pure}} = 0.003\,\frac{m^3}{s} \quad (10)$$

Using the correlation of Eq.6 the odour concentration of the biogas can be evaluated – equal to 345’000 ou_E/m^3 – and consequently also the OER, as shown in Eq.21:

$$OER_{landfill} = c_{od} * Q_{LFG} = 1023.5\ \frac{ou_E}{s} \quad (21)$$

The SOER is then calculated according to Eq.22, from which it is possible to determine the OER for each emissive cell. The outcome is the input for the CALPUFF dispersion model which provides the impact depicted in Fig.4 (left).

$$SOER_{landfill} = \frac{OER_{landfill}}{A_{tot}} = 0.005\ \frac{ou_E}{s*m^2} \quad (22)$$

Just looking at the OER and SOER values obtained with this method it is possible to foresee that the resulting impact will be much less significant than in the previous cases, and looking at Fig.4 makes it visually evident. It is important to highlight that in all impact maps the concentration range represented is 1-10 ou_E/m^3, but in this particular case since the maximum value is lower than 1 ou_E/m^3, the selected range is 0.1-1 ou_E/m^3. A very low emission such as the one obtained in this scenario can be explained since the sampling campaigns have been conducted only on allotment 1, the oldest one that is closed since 1994 and this probably led to an under-estimation of the real impact of the landfill, which is still operational.

Figure 4.

3.4 Experimental Measure Of The Odour Concentration On The Landfill Surface

Adopting the same sampling methodology used in method 3 (Flux Chamber), in this case 11 air samples were collected from the site that underwent an olfactometric analysis in order to determine their odour concentration. The geometric mean of the odour concentrations was calculated and turned out to be 135 ou_E/m^3. The SOER was obtained as shown in Eq.23:

$$SOER = \frac{c_{od}[\frac{ou_E}{m^3}]*Q_{air}[\frac{m^3}{s}]}{A_{hood}[m^2]} = \frac{135*200}{1000*3600*0.25} = 0.03\ \frac{ou_E}{m^2 s} \quad (23)$$

Also in this situation both the OER and the resulting odour impact are very low, as can be seen in

Fig.4 (right). Methods 3 and 4 produce relatively coherent results, thus confirming the hypothesis of a correlation existing between odour concentration and CH_4 concentration. Even if both methods under-estimate the real emissions, because relying on data gathered only from allotment 1, the approaches involving experimental campaigns in the field with the Flux Chamber seem to be the most reliable tools for the assessment of odour emissions from landfill surfaces.

3.5 Assessment Of The OER As A Function Of The Wind Speed

In this scenario the landfill is assumed as a completely passive area source; thus conducing sampling by means of a Wind Tunnel. In this case 15 samples were collected and analysed, giving an average odour concentration of 218 ou_E/m^3. Then the SOER was evaluated according to Eq.24:

$$SOER = \frac{c_{od} * Q_{air}}{A_{WT}} = 1.21 \ \frac{ou_E}{m^2 s} \qquad (24)$$

In this case, the OER obtained needs to be pre-processed before being used in the dispersion model; it is necessary to recalculate it as a function of the actual wind velocity at each hour of the simulation time domain according to Eq.5.

In method 5 the wind speed v_2 is the velocity recorded at a meteorological station nearby, at a height of 10 m. The velocity v_1 is the velocity inside the Wind Tunnel, i.e. 3.5 cm/s. The obtained OER values are used as input of the dispersion model producing the impact shown in Fig.5 (left). It is possible to observe that the isopleths cover the whole area of the map. The odour impact is very high and, as discussed for methods 1 and 2, it is an overestimation with respect to the real situation.

In the last two scenarios – methods 6 and 7 – as previously mentioned, the wind speed used for the OER recalculation is the one evaluated at the source level, i.e. 2 m, with tailored wind profile models exploiting a Power Law and a Logarithmic Law, respectively. The resulting odour impacts obtained with the dispersion model CALPUFF can be observed in Fig.5 (centre and right).

Figure 5.

It is worth underlying that methods 5, 6, 7 all share a common flaw, given by the fact that they consider the landfill surface as a passive area source, and therefore the emissions as a function of the wind speed over the emitting surface. It is likely that the LFG emissions from landfill surfaces have a dependence on the meteorological parameters that may affect the phenomenon, but the assumption that there is a well-defined dependence on the wind speed – which is true for passive area sources – for this source typology, is groundless since in this case the driving phenomenon of the whole process is not forced convection.

3.6 Comparison Of The OER Obtained With The Different Methods

In order to compare the different approaches adopted, Tab.1 summarizes the OER values obtained with methods 2, 4 and 7. These three were picked since – among the proposed approaches – they look like the best LandGEM-based method, the best Flux-Chamber-based method and the best Wind-Tunnel-based method respectively. More in detail, Tab.1 highlights how the OER order of magnitude changes from one method to the next one. Relying on a careful consideration and on the direct experience, it is believed that the most reliable methods are methods 3 and 4: they are experimental methods involving direct measurement campaigns in the field with a tailored sampling system adopting a specifically designed Flux Chamber device.

4. CONCLUSIONS

The purpose of the present work was the investigation of specific methods for the quantification of odour emissions from landfill surfaces since up to date there are no codified and universally accepted methodologies to address this peculiar problem. In facts, landfills represent a particular type of area sources that cannot be considered nor fully active nor fully passive.

Table 1. Estimated OER comparison for methods 2, 4 and 7.

Cell Name	Cell UTM East Coordinates [m]	Cell UTM North Coordinates [m]	OER Mod. 2 [ou_E/s]	OER Mod. 4 [ou_E/s]	OER Mod. 7 [ou_E/s]
A01	**493808 E**	**5056844 N**	**5156.4**	**192**	**14532.3**
A02	**493881 E**	**5056871 N**	**5156.4**	**192**	**14532.3**
A03	**493953 E**	**5056899 N**	**5156.4**	**192**	**14532.3**
A04	**494029 E**	**5056930 N**	**5156.4**	**192**	**14532.3**
A05	**494095 E**	**5056955 N**	**5156.4**	**192**	**14532.3**
A06	**493774 E**	**5056904 N**	**5156.4**	**192**	**14532.3**
A07	**493845 E**	**5056932 N**	**5156.4**	**192**	**14532.3**
A08	**493917 E**	**5056962 N**	**5156.4**	**192**	**14532.3**
A09	**493993 E**	**5056991 N**	**5156.4**	**192**	**14532.3**
A10	**494060 E**	**5057016 N**	**5156.4**	**192**	**14532.3**
A11	**493733 E**	**5056973 N**	**5156.4**	**192**	**14532.3**
A12	**493805 E**	**5057001 N**	**5156.4**	**192**	**14532.3**
A13	**493877 E**	**5057029 N**	**5156.4**	**192**	**14532.3**
A14	**493552 E**	**5057059 N**	**5156.4**	**192**	**14532.3**
A15	**494016 E**	**5057092 N**	**5156.4**	**192**	**14532.3**
A16	**493692 E**	**5057041 N**	**5156.4**	**192**	**14532.3**
A17	**493764 E**	**5057069 N**	**5156.4**	**192**	**14532.3**
A18	**493837 E**	**5057097 N**	**5156.4**	**192**	**14532.3**
A19	**493911 E**	**5057128 N**	**5156.4**	**192**	**14532.3**
A20	**493650 E**	**5057109 N**	**5156.4**	**192**	**14532.3**
B01	**493724 E**	**5057138 N**	**2922.2**	**108.8**	**8235.7**
C01	**493796 E**	**5057166 N**	**3931.7**	**146.4**	**11080.9**
D01	**493870 E**	**5057196 N**	**4816.4**	**179.3**	**13574.1**
E01	**493921 E**	**5057225 N**	**3113.2**	**115.9**	**8773.9**
F01	**493609 E**	**5057177 N**	**1728.2**	**64.4**	**4870.6**
G01	**493682 E**	**5057206 N**	**4146**	**154.4**	**11684.9**
H01	**493756 E**	**5057236 N**	**4146**	**154.4**	**11684.9**
I01	**493830 E**	**5057266 N**	**4413.5**	**164.3**	**12438.8**
J01	**493538 E**	**5057150 N**	**3741.6**	**139.3**	**10545**
K01	**493558 E**	**5057108 N**	**1423.6**	**53**	**4012.3**
L01	**493590 E**	**5057055 N**	**3029.4**	**112.8**	**8537.8**
M01	**493622 E**	**5057001 N**	**1482.5**	**55.2**	**4178.1**
N01	**493964 E**	**5057166 N**	**513.2**	**19.1**	**1446.4**
O01	**493674 E**	**5056935 N**	**1031.3**	**38.4**	**2906.5**
P01	**493526 E**	**5057177 N**	**1218.2**	**45.4**	**3433.3**
Q01	**493644 E**	**5057246 N**	**4060.6**	**151.2**	**11444.2**
Q02	**493715 E**	**5056895 N**	**4060.6**	**151.2**	**11444.2**

Q03	**493529 E**	**5057202 N**	**4060.6**	**151.2**	**11444.2**
Q04	**493748 E**	**5057281 N**	**4060.6**	**151.2**	**11444.2**
R01	**493881 E**	**5057279 N**	**3096.2**	**115.3**	**8726.2**

Different methods for the evaluation of odour emissions from landfill surfaces were developed and investigated. At first the LandGEM-based method was considered and a new possibility was explored modifying the default US-EPA software. The improved software designed allows to consider the two most significant input parameters of the LandGEM model variable yearly according to a set of aspects such as waste quality and composition. The new software shows an improvement with respect to the standard version of LandGEM, reducing the over-estimation by 10%. This improvement does not fix the underlying flaws of the concept of using a model for the estimation of the LFG generation for environmental emission assessment purposes (Capelli et al., 2014).

Another novel feature of the research is the optimization of the OER recalculation procedure involved in the methods relying on measurements with the Wind Tunnel. The changes also in this case led to an improvement of the previous situation but ultimately proved that anyhow the application of the Wind Tunnel to landfills, i.e. their assimilation to passive area sources, even though they characterized by a minimal yet non-negligible emissive flow which is not affected by forced convection, leads to an over-estimation of the OER.

Another aspect of the work entailed the estimation of the odour concentration of the LFG emitted through the landfill surface by means of specific olfactometric campaigns aiming to correlate odour and CH_4 concentration of the emitted LFG. The found correlation even though not exceptional is satisfactory, but further studies will be required in order to increase data robustness. In the future probably the samples should be collected not only in allotment 1 (closed), but in all allotments including the still active one.

Finally, the most significant result of the present work was the clear statement that experimental campaigns on site are fundamental for these kind of evaluations. Moreover, two sampling systems, i.e. Static Hood and Flux Chamber, were designed and tested, and the optimal sampling procedures were defined for the two devices; this led to the determination of a precise chain of actions for both the Static Hood and the Flux Chamber measurements.

Actually, it is here necessary to stress that the proposed emission models will have to be further compared and weighed by means of specific validation measurement campaigns in the field involving for instance field inspections, questioning and/or electronic noses (Capelli et al., 2013). Moreover, future investigations and experimental campaigns will need to span on larger temporal scales in order to be able to highlight other aspects affecting emissions such as seasonal effects and dependence on meteorological conditions.

REFERENCES

Alexander A., Burklin C., Singleton A., 2005. Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide, US EPA-600/R-05/047, Washington DC.

Balling R.C., Reynolds C.E., 1980. A model for evaluating the dispersion of wastewater plant odors. Water Pollut. Control 52, 2589-2593.

Capanema M. A., Cabana H., Cabral A. R., 2014. Reduction of odours in pilot-scale landfill biocovers. Waste Manage. 34, 770-779. DOI 10.1016/j.wasman.2014.01.016.

Capelli L., Sironi S., Del Rosso R., Centola P., 2009. Design and validation of a Wind Tunnel system for odour sampling on liquid area sources. Water Sci. Technol. 59, 1611-1620. DOI 10.2166/wst.2009.123.

Capelli L., Sironi S., Barczak R., Il Grande M., Del Rosso R., 2012. Validation of a method for odor sampling on solid area sources. Water Sci. Technol. 66, 1607-1613. DOI 10.2166/wst.2012.361.

Capelli L., Sironi S., Del Rosso R., Guillot J.-M., 2013. Measuring odours in the environment vs. dispersion modelling: A review. Atmos. Environ. 79, 731-743. DOI 10.1016/j.atmosenv.2013.07.029.

Capelli L., Sironi S., Del Rosso R., Magnano E., 2014. Evaluation of landfill surface emissions. Chem. Eng. Trans. 40, 187-192. DOI 0.3303/CET1440032.

Cook N.J., 1997. The Deaves and Harris ABL model applied to heterogeneous terrain. J. Wind Eng. Ind. Aerod. 66, 197–214.

D.G.R. 15 febbraio 2012 e n. IX/3018 Regione Lombardia, 2012. Determinazioni generali in merito alla caratterizzazione delle emissioni gassose in atmosfera derivanti da attività a forte impatto odorigeno, pp. 20e49. Bollettino Ufficiale 20 febbraio 2012.

Drew D.R., Barlow J.F., Lane S.E., 2013. Observations of wind speed profiles over Greater London, UK, using a Doppler lidar. J. Wind Eng. Ind. Aerod. 121, 98-105, DOI 10.1016/j.jweia.2013.07.019.

Frechen F.B., Frey M., Wett M., Löser C., 2004. Aerodynamic performance of a low-speed Wind Tunnel. Water Sci. Technol. 50, 57-64.

Hobson J., 1995. The odour potential: a new tool for odour management. Water Environ. J. 9, 458-463. DOI 10.1111/j.1747-6593.1995.tb01483.x.

Jiang J.K., Bliss P.J., Schulz T.J., 1995. The development of a sampling system for determining odor emission rates from area surfaces: Part I. aerodynamic performance. J. Air Waste Manage. 45, 917–922.

Jiang J.K., 1996. Concentration measurement by dynamic olfactometer. J. Water Environ. Tech. 8, 55-58.

Jiang J.K., Kaye R., 2001. Sampling techniques for odour measurement. Odours in Wastewater Treatment: Measurement, Modelling and Control, IWA Publishing, London.

Klenbusch M.R., 1986. Radian Corporation for the US EPA. Measurement of gaseous emission rates from land surfaces using an emission isolation flux chamber, US EPA, Las Vegas.

Koe L.C.C., 1989. Sewage odors quantification. Encyclopedia of Environmental Control Technology, Wastewater Treat. Technol. 3, cd P.N. Cheremisinoff, 423-446. Gulf Publishing Company, Houston.

Palmiotto M., Fattore E., Paiano V., Celeste G., Colombo A., Davoli E., 2014. Influence of a municipal solid waste landfill in the surrounding environment: Toxicological risk and odor nuisance effects. Environ. Int. 68, 16-24. DOI 10.1016/j.envint.2014.03.004.

Rachor I.M., Gebert J., Grongroft A. & E., Pfeiffer M., 2013. Variability of methane emissions from an old landfill over different time-scales. Eur. J. Soil Sci. 64, 16–26. DOI DOI: 10.1111/ejss.12004.

Scire J.S., Strimaitis D.G., Yamartino R.J., Zhang X., 2000. A user's guide for the CALPUFF dispersion model (Version 5), Earth Technology Inc., Concord.

Schauberger G., Piringer M., Schmitzer R., Kamp M., Sowa A., Koch R., Eckhof W., Grimm E., Kypke J., Hartung E., 2012. Concept to assess the human perception of odour by estimating short-time peak concentrations from one-hour mean values. Reply to a comment by Muller et al. Atmos. Environ. 54, 624-628.

Sironi S., Capelli L., Centola P., Del Rosso R., Il Grande M., 2005. Odour emission factors for assessment and prediction of Italian MSW landfills odour impact. Atmos. Environ. 39, 5387-5394. DOI 10.1016/j.atmosenv.2005.05.023.

Sironi S., Capelli L., Del Rosso R., 2014. Odor Emissions. Reference Module in Chemistry, Molecular Sciences and Chemical Engineering, Elsevier Inc.

Sohn J.H., Smith R., Yoong E., Leis J., Galvin G., 2003. Quantification of odours from piggery effluent ponds using an electronic nose and an artificial neural network. Biosyst. Eng. 86, 399–410. DOI http://dx.doi.org/10.1016/j.biosystemseng.2003.09.003.

Stordeur R.T., Stordeur C.M., Levine S.P., Hoggatt J.H., 1981. A new microprocessor-controlled dynamic olfactometer. J. Air Waste Manage. 31, 377-380. DOI 10.1080/00022470.1981.10465232.

Tieleman, H.W., 2008. Strong wind observations in the atmospheric surface layer. J. Wind Eng. Ind. Aerod. 96, 41–77. DOI 10.1016/j.jweia.2007.03.003.

VDI, 2011. Olfactometry Static Sampling, VDI 3880, Dusseldorf.

Ying D., Chuanyu C., Bin H., Yueen X., Xuejuan Z., Yingxu C., Weixiang W., 2012. Characterization and control of odorous gases at a landfill site: A case study in Hangzhou, China. Waste Manage. 32, 317-326. DOI 10.1016/j.wasman.2011.07.016.

FIGURES

Figure 1:

Figure 2:

Figure 3:

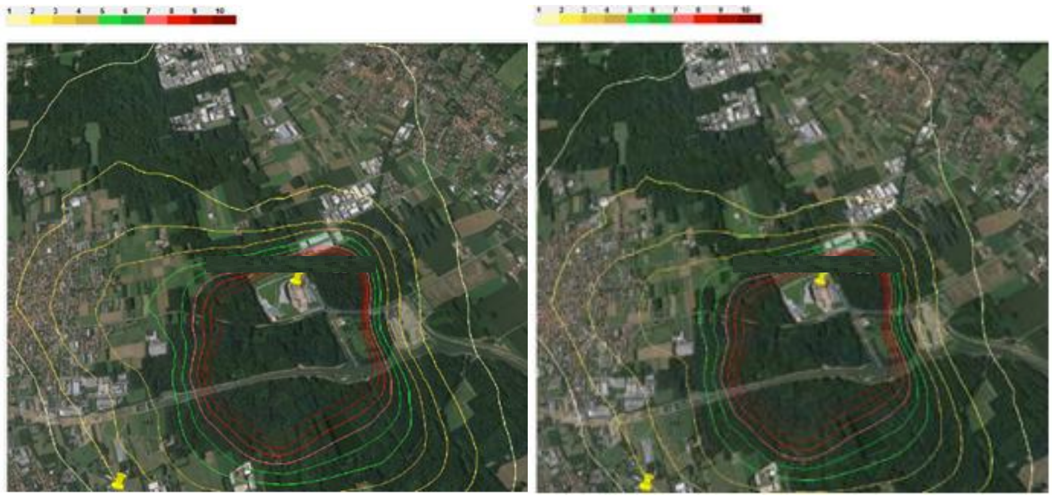
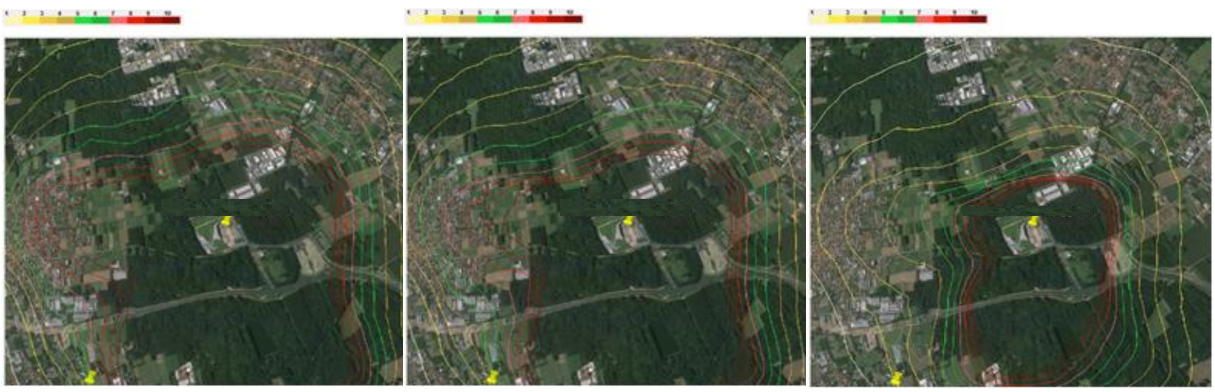


Figure 4:

Figure 5:



Highlights for the article (<85 characters/highlight):

- Odour emission assessment from landfills is important for landfill operation and management.
- Different methods for the evaluation of odour emissions from landfills were inspected.
- A new LandGEM-like software was developed for LFG generation assessment.
- One main outcome is that experimental campaigns on site are fundamental for emission assessment.
- Two sampling systems were designed and tested and the optimal sampling procedures were defined.

Figure captions:

Figure 1. Static hood: picture of the static hood used for static sampling; design based on the ones proposed by the UK EA and by Rachor.

Figure 2. Flux chamber: picture of the flux chamber used for fluxed sampling; design based on the US EPA guidelines.

Figure 3. Odour dispersion modelling results A: Odour impacts predicted with methods 1 (left) and 2 (right).

Figure 4. Odour dispersion modelling results B: Odour impacts predicted with methods 3 (left) and 4 (right).

Figure 5. Odour dispersion modelling results C: Odour impacts predicted with methods 5 (left), 6 (centre) and 7 (right).