INFLUENCE OF MODELLING CHOICES ON THE RESULTS OF LANDFILL ODOUR DISPERSION

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ABSTRACT: Despite the great advantages associated with the use of dispersion models for odour impact assessment from several types of plants, there are still some important issues related to the method uncertainty. Each of the input datasets required by the dispersion model represents a possible source of uncertainty. In the case of odour dispersion modelling, the emission data input for the model is represented by the Odour Emission Rate (OER), expressed as unit of odours emitted per unit time. Source term characterization and the estimation of the OER typically represent the most critical step and thus the highest contribution to the overall uncertainty. Moreover, another important element of uncertainty when modelling emissions from landfill surfaces is given by the geometrical implementation of the emission source in the dispersion model, which entails the definition of the initial dimensions of the emission, which is particularly critical in the case of large area sources. This paper aims to discuss the uncertainty issues related to the use of dispersion models for the evaluation of landfill odour impacts, thereby focusing on the two above mentioned parameters, i.e. the OER and the emission initial vertical dimension. The results of this study show that different modelling choices may result in modelled odour concentrations at receptors that may differ by up to a factor 3. This variability shoudn't produce distrust in the method, but instead point out the importance that odour dispersion modelling studies are carried out by experts having a deep knowledge of the mechanisms that originate the emissions.

Keywords: odour emissions, olfactometry, CALPUFF, dispersion model, odour sampling, area source

1. INTRODUCTION

In the last decades, an increase of population's awareness towards air quality issues has been occurring. This brought to include odours, which usually negatively affect human well-being without necessarily having an adverse effect on health (Sucker et al., 2001; Zhao et al., 2015), among atmospheric pollutants that are subject to control and regulations in many countries (Brancher et al., 2017). Indeed, due to the fact that residential areas are often very close to industrial activities, odours are nowadays the major cause of complaints to local authorities (Henshaw et al., 2006; Marchand et al., 2013), and in many cases thy become the limiting factor for the exercise of existing plants or for the realization of new ones. This is particularly true for plants related to the treatment and disposal of wastes, whose odour emissions are a cause of concerns for the near-living population (Marchand et al., 2013; Sironi et al., 2006). Among those, landfills are particularly critical from the point of view of the lamented odour nuisance (Che et al., 2013; Sakawi et al., 2017), thus requiring specific protocols for odour control and measurement (Chemel et al., 2012; Lucernoni et al., 2016; Sarkar et al., 2003; Tansel et al., 2019).

As already mentioned, odours are currently subject to control and regulation in many countries. Due to their capability to simulate how odour disperses from the emissions sources into the atmosphere, and therefore to calculate ground odour concentration values in the simulation space-time domain, dispersion models represent the preferred approach adopted in most regualtions concerning odours around the world (Brancher et al., 2017). In some cases, odour regulations specify the minimum distance from the closest inhabited area where possible odour-producing industrial or agricultural facilities can be located (Brancher et al., 2019; Capelli et al., 2013). Minimum distances are typically calculated by directly applying dispersion models or by using simplified mathematical expressions containing specific coefficients derived from dispersion modelling (Schauberger et al., 2012a, 2012b). In other cases, regulations fix acceptability standards in terms of the frequency with which a given odour concentration is exceeded (Brancher et al., 2017; Capelli et al., 2013).

Despite the great advantages associated with the use of dispersion models for odour impact assessment from several types of sources, there are still some important critical aspects that require to be studied. One open issue related to odour dispersion modelling is validation (Hayes 2006), which is particularly complex due to the difficulty of measuring odours in the environment (Capelli et al., 2013, 2018). Another very critical aspect is the uncertainty associated with the application of dispersion models for odour impact assessment (Brancher et al., 2019; Oettl et al., 2018).

Besides the choice of the dispersion model, which affects the resulting impacts (Piringer et al., 2016), within the same model, there are different aspects that may produce significant discrepancies in the modelling outputs. In general, dispersion models require three types of input data: emission data, topographic, and meteorological data of the site, which are combined together by the model in order to estimate how pollutant emissions are diluted and transported into the atmosphere. Each of these input datasets represents a possible source of uncertainty, together with the selection of other modelling parameters that depend on the dispersion model used. In the case of odour dispersion modelling, the emission data input for the model is represented by the Odour Emission Rate (OER), expressed as unit of odours emitted per unit time (Capelli et al., 2013). This datum shall be combined with the geometrical and physical parameters of the source for a complete source characterization, which is needed by any dispersion model. For some type of sources, source term characterization and the estimation of the OER may be extremely complex. Such cases include for instance sources having variable emissions over time, whereby it is difficult to associate a specific OER to every hour of the simulation domain, or diffuse sources, for which the the emitted air flow is hardly estimated. For this reason, source term characterization typically represents the most critical step and thus the highest contribution to the overall uncertainty in the implementation of an odour dispersion model (Capelli et al., 2014).

An example of source for which characterization is particularly diffucult are landfill surfaces. Indeed, in the case of landfills, the determination of odour emissions is a quite coplex and still debated task (Lucernoni et al., 2017). Even assuming that the emission of odour is associated mainly with the emission of landfill gas (LFG) that escapes the collection system (Chemel et al., 2012; Saral et al., 2009), up to now, no universally accepted methodology for evaluating the OER associated with this emission source has been established, as already discussed in previously published work (Lucernoni et al., 2017; Capelli and Sironi, 2018).

Moreover, another important element of uncertainty when modelling emissions from landfill surfaces is the geometrical implementation of the emission source in the model, which entails the definition of the initial dimensions of the emission, and thus is particularly critical in the case of large area sources.

This paper has the aim to discuss the uncertainty issues related to the application of dispersion modelling to a specific case study regarding the assessment of the odour impact from a landfill with a surface of 55’000 m^2. For the study, it was decided to apply the CALPUFF dispersion model, which is commonly used for regulatory purposes in Italy (Capelli et al., 2018; Ranzato et al., 2012).

More in detail, this paper focuses on two aspects of uncertainty. On one hand, it compares the different OER values obtained by using two different sampling methods, which are both applicable for odour sampling on landfill surfaces (Capelli et al., 2018; Lucernoni et al., 2017). The second aspect that is investigated is a parameter that is required specifically by the CALPUFF model when modelling area sources: the so called “initial vertical sigma” $\sigma_{Z,0}$, which is related to the emission vertical dimension.

The present work, besides recalling some basic principles for the selection of the sampling method and the definition of the source geometry, shows to which extent different choices regarding the model setting may affect its outputs, and thus the modelled odour impact of the studied landfill.

2. MATERIALS AND METHODS

2.1 Case study description

The selected case study regards the odour impact assessment relevant to a landfill having an emitting surface hypothesized equal to 55’000 m^2. Since the principal aim of the study aim is to make considerations about the influence of the choice of some critical modelling parameters on the outputs, it was decided to limit the evaluations to the emissions from the closed landfill surface, in order to avoid introducing other variables and thus other possible sources of uncertainty. By the way, due to the large surface of the latter (55’000 m^2) compared to the daily tipping area (about 1’000 m^2), the closed landfill surface can reasonably be assumed to be the main source of odour emissions from the studied landfill (Lucernoni et al., 2016).

The dispersion of the odour emissions from the landfill surface was evaluated using the CALPUFF model (Scire et al., 2000). CALPUFF is a multilayer, multispecies, non-steady-state, puff dispersion model, which is currently the dispersion model that is most often used in Italy for odour impact assessment evaluations and regulatory purposes (Capelli et al., 2018; Ranzato et al., 2012).

The meteorological data used for the study are 3D hourly data processed by means of the WRF (Weather Research and Forecasting) model with 1 km resolution relevant to the studied area relevant to the year 2015. The meteorological domain and the simulation domain were set equal, comprising an area of 4000 m x 4000 m, with a resolution of 100 m, giving a total of 1600 horizontal cells. 10 cells were considered on the vertical plane, giving a total of 16000 cells considered for the study.

The emission data were derived from one olfactometric sampling campaign carried out on the landfill surface, as described in the next paragraph.

2.2 Odour sampling methods

Up to now, no universally accepted methodology for sampling and assessing odour emissions from landfill surfaces has been established (Lucernoni et al., 2017; Capelli et al., 2018).

As a general rule, the most common approach to assess both odour and landfill gas emissions from landfill surfaces involves the use of sampling hoods, such as static hoods, flux chambers, or wind tunnels (Di Trapani et al., 2013; Lucernoni et al., 2016, 2017; Rachor et al., 2013; Schroth et al., 2012).

Wind tunnels are the “official” method foreseen by Italian local guidelines about odour impact assessment for odour sampling on passive area sources (Capelli et al., 2018). The main differences between wind tunnels (WTs) and flux chambers (FCs) concern the air flow rate at which the two systems are operated:

- In WTs the air flow is directional, whereas in FCs the inlet flux is mixed inside the hood;
- The typical air flow for WTs is about one order of magnitude higher than the air flow used in FCs.

Previous recent studies on the matter have proven FCs to provide a better representation of odour emissions from landfill surfaces (Lucernoni et al., 2017).

Since the aim of his study is to evaluate the effect of the most significant sources of uncertainty for the landfill odour impact assessment, it was decided to include the choice of the sampling method among the aspects to be evaluated. For this reason, both a WT and a FC were used for this study, and the specific odour emission rates (SOER) evaluated with both methds were compared.

The WT used for this study has a base area of 0.125 m^2, and is operated with an air flow of 40 L/min. The FC has the same base area as the WT (i.e. .125 m^2) and is operated with an air flow of 4 L/min.

For both sampling methods, the SOER can be evaluated as follows:

$$SOER = \frac{c_{od} \cdot Q_{air}}{A_{base}}$$

Where SOER is the Specific Odor Emission Rate ($ou_E/m^2/s$), c_{od} the measured odor concentration (ou_E/m^3), Qair the air flow rate inside the hood (m^3/s) and A_{base} the base area of the sampling hood (m^2). The SOER value is the parameter that is used as input for dispersion modelling. Odour concentration was measured according to the EN 13725:2003.

For olfactometric sampling, the landfill surface was divided into 9 sub-areas (Figure 1, left). One sample was collected at the centre of each sub-area.

2.3 Definition of the initial vertical dispersion coefficient σ

When characterizing an area source in the CALPUFF model, the model requires the definition of some dimensional parameters. Besides the source area and height, for an area source it is necessary to define the so called "initial vertical sigma", $\sigma_{Z,0}$, which is a measure of the vertical dimension of the emission.

Considerations about the setting of this parameter can be found for Gaussian models (US EPA, 2004, 2011). The most common rule for the evaluation of the $\sigma_{Z,0}$, is to set it equal to the vertical dimension of the source (i.e., the source height), divided by 2.15, as suggested in Table 3-2 of the US EPA User's guide for the regulatory model AERMOD (US EPA, 2011) (the coefficient of 2.5 comes from the Gaussian distribution of the pollutant concentration inside the plume). Despite this simple rule, considerations about the correct value for the $\sigma_{Z,0}$ are not so easy.

Indeed, the $\sigma_{Z,0}$ represents the initial vertical dimension of the plume (for a Gaussian model; in CALPUFF $\sigma_{Z,0}$ represents the initial vertical dimension of the puff at the emission, but considerations are similar). Therefore, it is clear that in general the $\sigma_{Z,0}$ is related directly to the source height. However, the source height is not the only parameter that may affect the initial vertical dimension of the plume, especially in the case of particular sources, as it is also mentioned in the AERMOD User's Guide (US EPA, 2011). The user's guide specifies that in cases in which the emission may be turbulently mixed near the source and therefore occupy some initial depth, then the $\sigma_{Z,0}$ shall be set as to account for this initial vertical dimension of the emission, although, unfortunately, it is not specified how to do that. Indeed, in the US EPA's Haul Road Workgroup final report to the Air Quality Modeling Group, different relationships for the calclulation of the $\sigma_{Z,0}$ can be found, but unfortunately they are specificic for the emissions from road transport. However, this document clearly shows that the $\sigma_{Z,0}$ is not necessarily a function of the sole source height.

In the case of area sources, $\sigma_{Z,0}$ is the initial vertical dimension of the area source plume. In the case of passive area sources such as wastewater treatmen tanks, which are typically relatively small (compared to a landfill), and the emission occurs passively due to natural convection from the liquid surface to the atmosphere, there is no reason to assume that turbulence may play an important role and thus provide the plume with a considerable initial dimension.

However, the case of landfills is different. First, landfills cannot be considered equally to passive area sources, because of the different mechanisms that regulate the emission from the surface to the atmosphere. Indeed, there is a small – but not negligible – flux of gas that crosses the landfill body and is emitted into the atmosphere trhough the landfill surface. For this reason, landfills should rather be considered as "semi-passive" area sources. Second, landfills are typically very large area sources (in the considered case study 55'000 m^2), characterized by an uneven surface; even considering the same parcel, the landfill surface can have different heights due to the presence of reliefs. Moreover, the landfill surface is typically scattered with "obstacles", such as LFG extraction wells. All these elements contribute to the presence of certain degree of turbulence over the landfill surface, which makes that the initial plume emitted by the landfill shall have a certain height. Finally, due to the large dimensions of the landfill, it can reasonably be supposed that the initial plume height (PH) shall somehow also be related to the landfill horizontal dimensions. Higher plumes would be assumed to be emitted from very large landfills, where the turbulent contribution is higher and the pollutants are carried along the landfill surface for all its length to form the initial emission puff.

However, because of the lack of precise rules for the evaluation of the $\sigma_{Z,0}$ in such complex cases, and also because of the complexity of the geometrical features of the landfill, it is not possible at this stage to establish one unique and unequivocal way for setting the value of the $\sigma_{Z,0}$ in the model.

For these reasons, it was deemed useful to evaluate how the choice of different values of $\sigma_{Z,0}$, selectd within a reasonable range, may affect the model results.

For this purpose, the model was run considering the following values of $\sigma_{Z,0}$: 1, 2, 5, 10, 20, and 30 m, respectively. Besides comparing the different odour impact maps resulting from the model runs, further evaluation were made by comparing the odour concentrations calculated by the model on a set of selected receptors. More in detail, a receptor nest was created by setting 8 receptors at distances of 300, 500, 750 and 1000 m from the source centre, respectively, giving a total of 32 receptors, according to the scheme shown in Figure 1 (right).

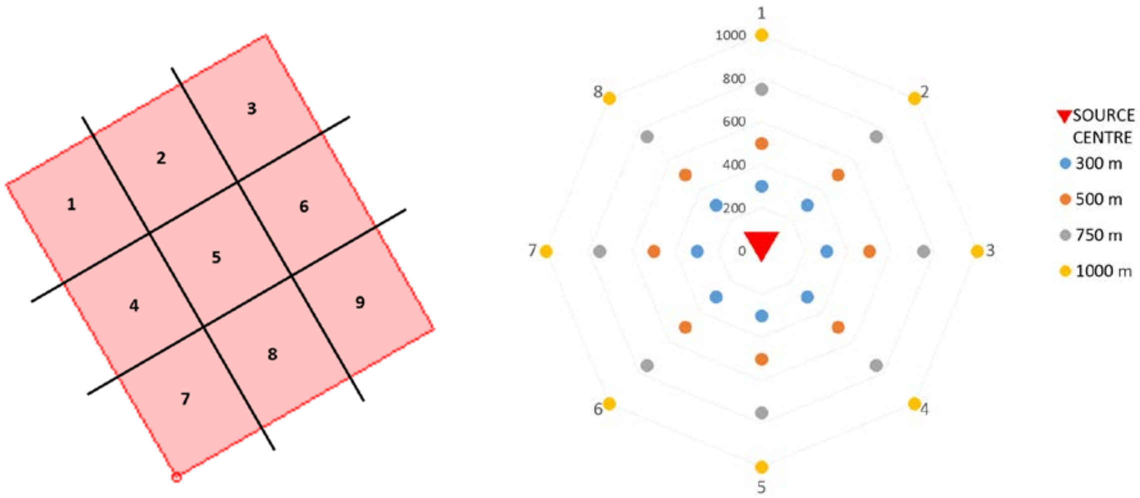

Figure 1. Division of the landfill into 9 sub-areas for olfactometric sampling (left) and location of the 32 discrete receptors selected for comparison of the model outputs obtained with different values of $\sigma_{Z,0}$ (right)

3. RESULTS AND DISCUSSION

3.1 Odour sampling on the landfill surface

As already mentioned, olfactometric sampling were performed both with a Flux Chamber (FC) and with a Wind Tunnel (WT). In order to compare the results obtained with the two methods, Table 1 reports the results of the olfactometric measurements carried out on the landfill site in terms of odour concentration (in ou_E/m^3) and deriving SOER, which was evaluated as described in section 2.2.

The lower odour concentration values relevant to the measurements of the samples collected by means of the wind tunnel are due to the higher operational air flow, which entails a higher dilution of the sample collected at the hood outlet. However, since the SOER is related to the product between the odour concentration and the air flow, for the SOER an opposite trend is observed: the SOER derived from the FC measurements is about three times lower than the SOER resulting from the wind tunnel measurements.

This in turn means that, depending on the sampling method adopted, the resulting emission data to be used as inputs for dispersion modelling – and consequently the resulting ground concentrations- may vary by a factor of 3. This clearly represents a significant source of uncertainty: the respect or breach of acceptability criteria, as well as the determination of suitable separation distances, may totally be overturned by such a factor of uncertainty.

As previously mentioned, there are recent studies regarding the estimation of odour emissions from landfill surfaces proving that WTs tend to overestimate emissions (Lucernoni et al., 2016, 2017). This overestimation is assumed to be associated with the fact that the odour concentration values that are measured by means of WTs are in some cases so low that they are likely to be attributable more to the odour of the landfill soil coverage than to emission of LFG through the landfill surface (Lucernoni e t al., 2016). Indeed, also in this case, among the odour concentrations of the samples collected by means of the WT, there are some values that are so low that they are close to the lower detection limit for dynamic olfactometry (Lucernoni et al., 2016). This is less the case for FC measurements, whereby the odour concentrations are considerably higher, and thus should ecxceed the interference of possible background odours.

Table 1. Results of the olfactometric measurements of the odour samples collected over the landfill surface by means of a flux chamber (FC) and of a wind tunnel (WT)

Sampling point	FC	FC	WT	WT
	Measured c_{od} [ou_E/m^3]	SOER [$ou_E/m^2/s$]	Measured c_{od} [ou_E/m^3]	SOER [$ou_E/m^2/s$]
1	750	0.40	140	0.75
2	410	0.22	81	0.43
3	270	0.14	60	0.32
4	66	0.04	52	0.28
5	1330	0.71	240	1.28
6	840	0.45	310	1.65
7	310	0.17	88	0.47
8	860	0.46	280	1.49
9	380	0.20	210	1.12
Geometric average	440	0.23	134	0.71

3.2 Evaluation of the effect of different values of $\sigma_{Z,0}$

As described in section 2.3, the model was run by setting different values for the $\sigma_{Z,0}$ in order to evaluate the influence of this parameter on the model outputs, i.e. on the simulated odour impact of the landfill on the surrounding territory.

The odour impact resulting from dispersion modelling was evaluated in terms of the 98th percentile hourly peak odour concentration values simulated by the model on the receptor grid, in conformity with the prescriptions of the local regulations and guidelines about odour pollution that are currently in force in

Italy.

Figure 2 shows the maps of the 98th percentile hourly peak odour concentration values simulated by the model runs performed by setting different values for $\sigma_{Z,0}$, i.e. 1, 5, 10 and 30 m. In order to allow for comparison, the same scale was adopted for the different maps.

It can be observed that the extent of the odour impact shrinks when $\sigma_{Z,0}$ increases: a higher initial dimension of the emission entails a better dispersion of the odour, and thus a lower impact. This behaviour is particularly evident for the highest value of $\sigma_{Z,0}$ tested (i.e. 30 m), whereas such differences are less pronounced in the maps resulting from the simulations with $\sigma_{Z,0}$ of 1, 5 and 10 m. Indeed, the higher differences are observed close to the source, where the maximum odour concentrations modelled decrease significantly, whereas the shape and the extent of the iso-concentration lines at higher distance from the source look more similar between the different maps.

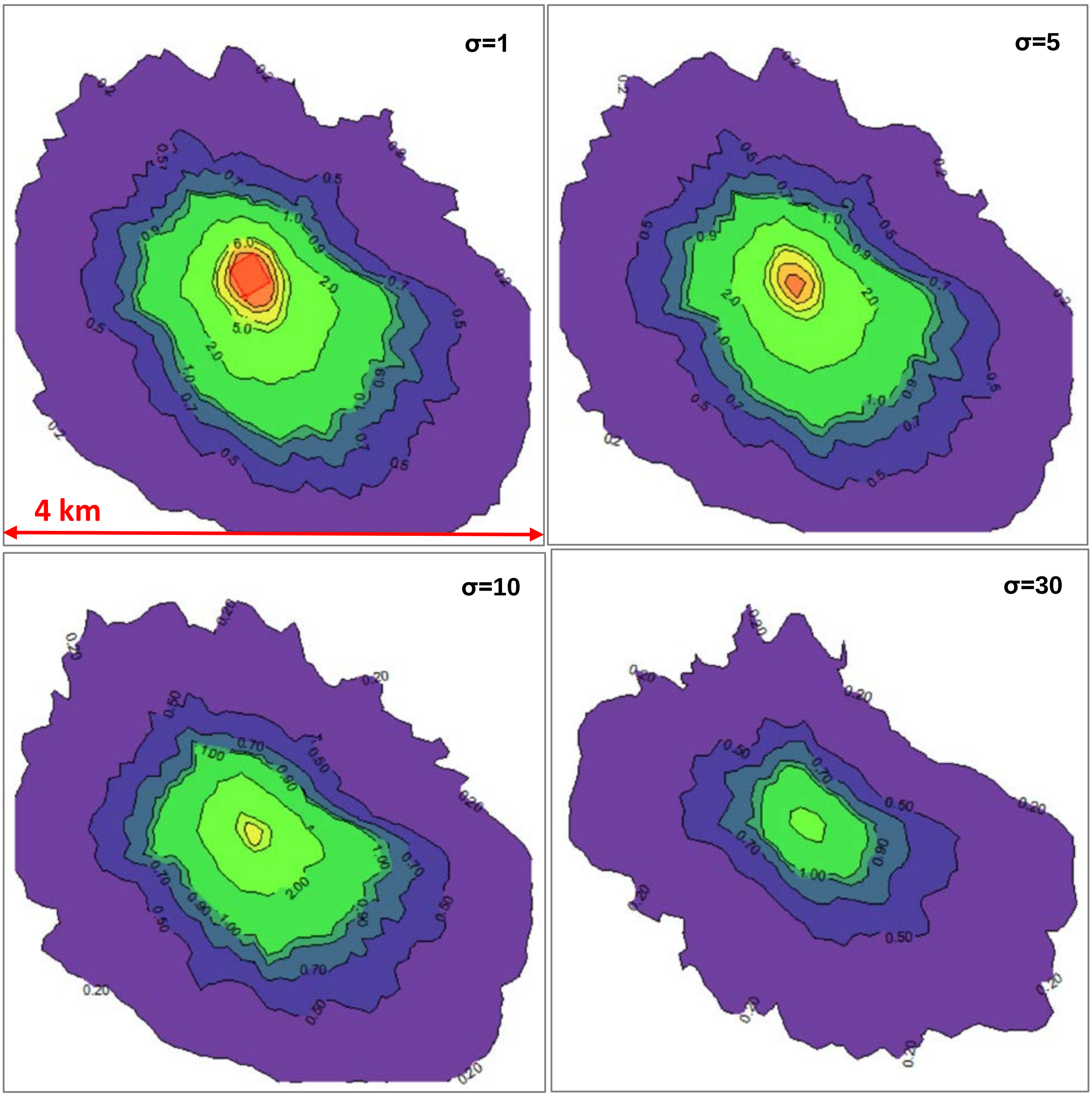

Figure 2. Maps of the 98th percentile of the hourly peak concentrations resulting from the model runs performed by setting the source $\sigma_{Z,0}$ equal to 1, 5, 10 and 30 m, respectively

In order to better visualize the differences between the conditions tested, the odour concentrations calculated by the model on a set of different receptors located at different distances from the source were evaluated. The 98th hourly peak odour concentration values evaluated for the different values of $\sigma_{Z,0}$ on the 32 receptors, selected as illustrated in section 2.3, are reported in Table 2.

The values reported in the table reflect what is observed from the maps. When considering the receptors at 300 m from the source centre, by passing from a $\sigma_{Z,0}$ of 1 m to a $\sigma_{Z,0}$ of 30 m, the resulting concentration on the receptor decreases by a factor 3-4. This effect is less pronounced at higher distances from the source, whereby the decrease is about the half. Nonetheless, such factors of uncertainty obtained for different values of $\sigma_{Z,0}$, are in general quite high. Assuming that an acceptability criterion of 5 ou_E/m^3 at the closest receptors is fixed for the studied area, then it is clearly visible that a different choice of the value of $\sigma_{Z,0}$ would result either in the respect or in the breach of this limit. This consideration is particularly important, since, as stated in the introduction, dispersion models are often used for regulatory purposes.

Table 2. 98th hourly peak odour concentration values calculated by the model for the different values of $\sigma_{Z,0}$ tested on the 32 discerete receptors selected at 300, 500, 750, and 1000 m from the source centre, respectively

Receptor	σ=1	σ=2	σ=5	σ=10	σ=20	σ=30
R1_300m	4.67	4.38	3.79	2.79	1.52	1.27
R2_300m	4.61	4.09	2.85	1.98	1.13	0.95
R3_300m	5.25	5.02	4.27	2.80	1.83	1.52
R4_300m	6.68	6.38	5.36	3.80	2.19	1.70
R5_300m	5.99	5.65	4.74	3.22	1.77	1.25
R6_300m	4.28	4.04	3.37	2.43	1.32	0.87
R7_300m	4.44	4.19	3.53	2.60	1.59	0.96
R8_300m	3.73	3.58	3.14	2.45	1.45	1.03
R1_500m	1.78	1.75	1.63	1.29	0.95	0.82
R2_500m	1.24	1.17	1.11	0.81	0.63	0.58
R3_500m	2.69	2.63	2.35	2.01	1.32	0.98
R4_500m	4.07	3.81	3.36	2.29	1.48	1.07
R5_500m	3.35	3.18	2.76	1.92	1.03	0.76
R6_500m	1.99	1.94	1.68	1.29	0.77	0.54
R7_500m	1.98	1.94	1.79	1.48	1.11	0.66
R8_500m	1.63	1.61	1.53	1.29	0.86	0.83
R1_750m	0.69	0.75	0.66	0.62	0.50	0.44
R2_750m	0.75	0.74	0.71	0.58	0.47	0.38
R3_750m	1.40	1.39	1.28	1.16	0.78	0.71
R4_750m	2.10	2.07	1.95	1.47	1.03	0.82
R5_750m	1.89	1.86	1.57	1.09	0.74	0.50
R6_750m	1.06	1.04	0.96	0.75	0.50	0.41
R7_750m	1.14	1.13	1.05	0.95	0.64	0.44
R8_750m	0.96	0.95	0.91	0.77	0.58	0.55
R1_1km	0.49	0.56	0.47	0.40	0.37	0.33
R2_1km	0.50	0.46	0.45	0.35	0.23	0.20
R3_1km	1.05	1.04	0.98	0.89	0.71	0.62
R4_1km	1.37	1.36	1.29	0.99	0.79	0.60
R5_1km	1.27	1.25	1.12	0.90	0.55	0.40
R6_1km	1.73	1.68	1.44	1.01	0.68	0.52
R7_1km	0.73	0.72	0.65	0.62	0.52	0.36
R8_1km	0.61	0.61	0.60	0.54	0.46	0.43

Given that the setting of the $\sigma_{Z,0}$ for landfill sources represents an important degree of freedom, it is very important to analyze the variability of outputs that derives from different possible – and reasonable – choices for this value. In this regard, it is important to highlight that, to the best of our knowledge, there is a lack of specific studies addressing this problem and discussing how to choose this parameter properly in order to obtain representative results.

4. CONCLUSIONS

Dispersion models are currently the most effective method for odour impact assessment for regulatory purposes as well as for the verification of the effect of mitigation strategies. For this reason, it is important to analyse the differences in the results that can be produced by operating different modelling choices.

On one hand, the choice of the method for the obtainment of olfactometric data to characterize the emissions from the landfill surface is particularly critical. Wind tunnels are the sampling method foreseen by Italian regulations on the matter, however, previous studies prove such systems to overestimate emissions. In this study, we found that wind tunnels produce odour emission rate values that are three times higher than those obtained with flux chambers. This would be reflected in the model outputs by giving three times higher concentrations at receptors.

Another critical parameter for area source characterization in the CALPUFF model is the so called “initial vertical sigma” $\sigma_{Z,0}$. Given that the definition of the $\sigma_{Z,0}$ for landfill sources represents an important degree of freedom when implementing the source term in a dispersion model, it is important to analyse and to be aware of the variability of results that derives from possible – and reasonable – choices for this value. The sensitivity analysis conducted for the proposed case study, involving a landfill with a surface of 55’000 m^2, shows that, for $\sigma_{Z,0}$ values ranging from 1 m to 30 m, modelled concentrations at receptors may vary by almost a factor 4 at 300 m from the source and by a factor 2 at a distance of 1 km.

This high variability shouldn’t produce a distrust in the method, but it should point out the importance of properly implementing the model. To do that, it is necessary to have a deep knowledge of the physical and chemical mechanisms that are related to the emission of odours from the studied sources, in order to be able to choose the most appropriate sampling strategy and define the initial dimensions of the emitted plume or puff within a narrow range. Thus, especially in the case verification of compliance to acceptability criteria, it is important that odour dispersion modelling studies are carried out by experts having a deep knowledge of the odour emissions under investigation.

REFERENCES

Brancher, M., Griffiths, K. D., Franco, D., & de Melo Lisboa, H. (2017). A review of odour impact criteria in selected countries around the world. Chemosphere, 168, 1531-1570. https://doi.org/10.1016/j.chemosphere.2016.11.160

Brancher, M., Piringer, M., Grauer, A. F., & Schauberger, G. (2019). Do odour impact criteria of different jurisdictions ensure analogous separation distances for an equivalent level of protection?. Journal of environmental management, 240, 394-403. https://doi.org/10.1016/j.jenvman.2019.03.102

Capelli, L., Sironi, S., Del Rosso, R., Bianchi, G., & Davoli, E. (2012). Olfactory and toxic impact of industrial odour emissions. Water Science and Technology, 66(7), 1399-1406. https://doi.org/10.2166/wst.2012.352

Capelli, L., Sironi, S., Del Rosso, R., & Guillot, J. M. (2013). Measuring odours in the environment vs. dispersion modelling: A review. Atmospheric Environment, 79, 731-743. https://doi.org/10.1016/j.atmosenv.2013.07.029

Capelli, L., Dentoni, L., Sironi, S., & Del Rosso, R. (2014). The need for electronic noses for environmental odour exposure assessment. Water Science and Technology, 69(1), 135-141. https://doi.org/10.2166/wst.2013.544

Capelli, L., & Sironi, S. (2018). Combination of field inspection and dispersion modelling to estimate odour emissions from an Italian landfill. Atmospheric environment, 191, 273-290. https://doi.org/10.1016/j.atmosenv.2018.08.007

Che, Y., Yang, K., Jin, Y., Zhang, W., Shang, Z., & Tai, J. (2013). Residents’ concerns and attitudes toward a municipal solid waste landfill: integrating a questionnaire survey and GIS techniques. Environmental monitoring and assessment, 185(12), 10001-10013.

Chemel, C., Riesenmey, C., Batton-Hubert, M., & Vaillant, H. (2012). Odour-impact assessment around a landfill site from weather-type classification, complaint inventory and numerical simulation. Journal of environmental management, 93(1), 85-94. https://doi.org/10.1016/j.jenvman.2011.08.016

Di Trapani, D., Di Bella, G. & Viviani, G. (2013). Uncontrolled methane emissions from a MSW landfill surface: Influence of landfill features and side slopes. Waste Management, 33, 2108-2115. https://doi.org/10.1016/j.wasman.2013.01.032

Hayes, E. T., Curran, T. P., & Dodd, V. A. (2006). A dispersion modelling approach to determine the odour impact of intensive poultry production units in Ireland. Bioresource technology, 97(15), 1773-1779. https://doi.org/10.1016/j.biortech.2005.09.019

Henshaw, P., Nicell, J., & Sikdar, A. (2006). Parameters for the assessment of odour impacts on communities. Atmospheric Environment, 40, 1016-1029. https://doi.org/10.1016/j.atmosenv.2005.11.014

Lucernoni, F., Tapparo, F., Capelli, L., & Sironi, S. (2016). Evaluation of an Odour Emission Factor (OEF) to estimate odour emissions from landfill surfaces. Atmospheric environment, 144, 87-99. https://doi.org/10.1016/j.atmosenv.2016.08.064

Lucernoni, F., Capelli, L., & Sironi, S. (2017). Comparison of different approaches for the estimation of odour emissions from landfill surfaces. Waste management, 63, 345-353. https://doi.org/10.1016/j.wasman.2016.09.041

Marchand, M., Aissani, L., Mallard, P., Béline, F., & Réveret, J. P. (2013). Odour and life cycle assessment (LCA) in waste management: a local assessment proposal. Waste and Biomass Valorization, 4(3), 607-617. https://doi.org/10.1007/s12649-012-9173-z

Oettl, D., Kropsch, M., & Mandl, M. (2018). Odour assessment in the vicinity of a pig-fatting farm using field inspections (EN 16841-1) and dispersion modelling. Atmospheric environment, 181, 54-60. https://doi.org/10.1016/j.atmosenv.2018.03.029

Piringer, M., Knauder, W., Petz, E., & Schauberger, G. (2016). Factors influencing separation distances against odour annoyance calculated by Gaussian and Lagrangian dispersion models. Atmospheric environment, 140, 69-83. https://doi.org/10.1016/j.atmosenv.2016.05.056

Rachor, I. M., Gebert, J., Gröngröft, A., & Pfeiffer, E. M. (2013). Variability of methane emissions from an old landfill over different time-scales. European journal of soil science, 64(1), 16-26. https://doi.org/10.1111/ejss.12004

Ranzato, L., Barausse, A., Mantovani, A., Pittarello, A., Benzo, M., & Palmeri, L. (2012). A comparison of methods for the assessment of odor impacts on air quality: Field inspection (VDI 3940) and the air dispersion model CALPUFF. Atmospheric environment, 61, 570-579. https://doi.org/10.1016/j.atmosenv.2012.08.009

Sakawi, Z., SA, S. M., Jaafar, O., & Mahmud, M. (2017). Community perception of odour pollution from landfills. Geografia-Malaysian Journal of Society and Space, 7(3).

Saral, A., Demir, S., & Yıldız, Ş. (2009). Assessment of odorous VOCs released from a main MSW landfill site in Istanbul-Turkey via a modelling approach. Journal of Hazardous Materials, 168(1), 338-345. https://doi.org/10.1016/j.jhazmat.2009.02.043

Sarkar, U., Longhurst, P. J., & Hobbs, S. E. (2003). Community modelling: a tool for correlating estimates of exposure with perception of odour from municipal solid waste (MSW) landfills. Journal of environmental management, 68(2), 133-140. https://doi.org/10.1016/S0301-4797(03)00027-6

Schauberger, G., Piringer, M., Jovanovic, O., & Petz, E. (2012a). A new empirical model to calculate separation distances between livestock buildings and residential areas applied to the Austrian guideline to avoid odour nuisance. Atmospheric environment, 47, 341-347. https://doi.org/10.1016/j.atmosenv.2011.10.056

Schauberger, G., Schmitzer, R., Kamp, M., Sowa, A., Koch, R., Eckhof, W., ... & Hartung, E. (2012b). Empirical model derived from dispersion calculations to determine separation distances between livestock buildings and residential areas to avoid odour nuisance. Atmospheric environment, 46, 508-515. https://doi.org/10.1016/j.atmosenv.2011.08.025

Schroth, M. H., Eugster, W., Gómez, K. E., Gonzalez-Gil, G., Niklaus, P. A., & Oester, P. (2012). Above-and below-ground methane fluxes and methanotrophic activity in a landfill-cover soil. Waste management, 32(5), 879-889. https://doi.org/10.1016/j.wasman.2011.11.003

Scire, J. S., Strimaitis, D. G., & Yamartino, R. J. (2000). A user's guide for the CALPUFF dispersion model. Earth Tech, Inc. Concord, MA, 10.

Sironi, S., Capelli, L., Céntola, P., Del Rosso, R., & Il Grande, M. (2006). Odour emission factors for the prediction of odour emissions from plants for the mechanical and biological treatment of MSW. Atmospheric Environment, 40(39), 7632-7643. https://doi.org/10.1016/j.atmosenv.2006.06.052

Sucker, K., Both, R., & Winneke, G. (2001). Adverse effects of environmental odours: reviewing studies on annoyance responses and symptom reporting. Water Science and Technology, 44(9), 43-51. https://doi.org/10.2166/wst.2001.0505

Tansel, B., & Inanloo, B. (2019). Odor impact zones around landfills: Delineation based on atmospheric conditions and land use characteristics. Waste Management, 88, 39-47. https://doi.org/10.1016/j.wasman.2019.03.028

US Environmental Protection Agency (2004). User's guide for the AMS/EPA regulatory model—AERMOD.

US Environmental Protection Agency (2011). Haul Road Workgroup final report to the Air Quality Modeling Group.

Zhao, Y., Lu, W., & Wang, H. (2015). Volatile trace compounds released from municipal solid waste at the transfer stage: evaluation of environmental impacts and odour pollution. Journal of hazardous materials, 300, 695-701. https://doi.org/10.1016/j.jhazmat.2015.07.081