

1 **Combination of field inspection and dispersion modelling to estimate odour**
2 **emissions from an Italian landfill**

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7

8 **ABSTRACT**

9 In the case of landfills, the determination of odour emissions is particularly complex. Up to now, no
10 universally accepted methodology for sampling and assessing emissions from landfill surfaces has been
11 established. Besides, the dependence of such emissions from some crucial environmental variables, such as
12 wind speed, has not been univocally defined yet. In this study, odour dispersion modelling and plume
13 inspections by human assessors were combined in order to estimate the odour emissions from a landfill in
14 Southern Italy. Two substantially different approaches were compared: the one that considers emissions as
15 a function of the wind speed blowing over the surface, counterposed to the one that considers odour
16 emissions as constant, in agreement with the most recent studies on the matter. The comparison of the
17 field assessments and the model clearly highlights that the first approach significantly overestimates the
18 landfill odour emissions, whereas the use of a constant odour emission rate results in a much better
19 correspondence between model outputs and field assessments, both in terms of shape and extension of
20 the determined odour plume extents.

21

22 Keywords: odour emission rate; odour impact assessment; plume method; olfactometry; landfill gas;
23 landfill surface emissions

24

25 **1. INTRODUCTION**

26 Since several decades now, odours are, among atmospheric pollutants, the major cause of population's
27 complaints to local authorities in many different contexts (Brambilla & Navarotto 2010; Hayes et al., 2014;
28 Henshaw et al., 2006). Odour pollution is nowadays a serious environmental (and in some cases also
29 health) concern (Claeson et al., 2013), and is currently subjected to specific regulation in many countries
30 (Loriato et al., 2012; Sironi et al., 2013; Brancher et al., 2017).

31 The existence of regulatory acceptability criteria entails the necessity to develop suitable methods for
32 odour assessment, debunking the common belief that odour characterization is more art than science
33 (Lucernoni et al., 2017a; Muñoz et al., 2010).

34 One of the odour impact assessment techniques that is most commonly applied and contemplated by
35 different regulations involves the use of the odour emission rate (OER), expressed as unit of odours emitted
36 per unit time, combined with topographic and meteorological data of the site, as input data for dispersion
37 models, which allow to estimate how odour emissions are diluted and transported into the atmosphere
38 (Capelli et al., 2013a; Brancher et al., 2017). The assessment of the OER relevant to an odour source
39 typically involves 3 phases: on-site sampling (Bockreis & Steinberg, 2005; Capelli et al., 2013b), sample
40 analysis (CEN EN 13725, 2003), and data elaboration for the evaluation of a representative OER (Hudson et
41 al., 2009; Capelli et al., 2013b).

42 In the specific case of area sources, for which sampling is typically conducted by means of fluxed hoods
43 (Bockreis & Steinberg, 2005; Capelli et al., 2013b), with the odour concentration it is possible to evaluate
44 the Specific Odour Emission Rate (SOER), that is the odour units emitted from the source per surface and
45 time unit [ou/m²/s] referred to the specific operating conditions used during sampling (Hudson et al., 2007;
46 Capelli et al., 2009). Specific models are then required in order to relate the SOER to real field conditions
47 (Lucernoni et al., 2017b).

48 In the case of landfills, the determination of odour emissions (in terms of OER or SOER) is particularly
49 complex. Even assuming that the emissions of odour is mainly associated with the unwanted emission of
50 landfill gas (LFG) that escapes the LFG collection system (Capelli et al., 2008; Chemel et al., 2012; Saral et
51 al., 2009), up to now, no universally accepted methodology for sampling and assessing LFG emissions from
52 landfill surfaces has been established (Babilotte et al., 2010; Fredenslund et al., 2010; Lohila et al., 2007;
53 Lucernoni et al., 2016a, 2017c; Mackie et al., 2009). Besides, the dependence of such emissions from some
54 crucial environmental variables has not been univocally defined yet, making the quantification of LFG
55 emissions for implementation in a dispersion model hardly applicable. If on one hand the dependence of
56 the OER from the wind speed for other types of area sources such as liquids has been studied and verified
57 experimentally (Capelli et al., 2009; Lucernoni et al., 2017b), proving that the OER is proportional to the
58 speed of the wind blowing over the surface with an exponent of 0.5 (in case of laminar flow) or 0.78 (in
59 case of turbulent flow), recent studies seem to point out that landfill surfaces need to be treated differently
60 (Lucernoni et al., 2016b). As a matter of fact, the mechanism that regulates emissions from landfill surfaces
61 is not forced convection but the presence of an endogenous gas flow due to the formation of LFG inside the
62 landfill body, which is not directly affected by the wind blowing over the surface (Lucernoni et al., 2017a).

63 The effects of the other environmental parameters mentioned in other studies has never been really
64 quantified up to now; on the contrary, the statements found in literature about the dependence of LFG
65 emissions on variables such as atmospheric temperature or soil humidity are sometimes contradictory
66 (Lucernoni et al., 2016c, Park et al., 2001; Rachor et al., 2013)

67 In a recent study, we tried to investigate and compare different approaches to estimate odour emission
68 rates from landfill surfaces (Lucernoni et al., 2017a). Thanks to the consolidated experience regarding the
69 odour impact of this particular landfill acquired over the years, it was possible to conclude that the most
70 reliable methods for the estimation of odour emissions from the landfill surface involve measurement
71 campaigns in the field with a tailored sampling hood system, either Flux Chamber or Static Hood. The use of
72 a Wind Tunnel showed an overestimation of the landfill OER, due to the fact that the emission is considered
73 as a function of the wind speed over the emitting surface, as it is for quiescent passive sources (Lucernoni

74 et al., 2017b), whereby for landfills the assumption of such dependency is groundless, since the driving
75 force of the emission phenomenon is not forced convection. However, as stated in the above mentioned
76 study, the evaluation of the best method for odour emission sampling is lacking of a specific validation in
77 the field. In general, the possibility of measuring odours in the field, both as a way for directly assessing
78 odour annoyance or for verifying that modelled odour concentrations correspond to the effective odour
79 perception by humans, is a quite complicated task (Capelli et al., 2013a).

80 For this reason, the attempt to validate odour dispersion models often entails the adoption of very specific
81 techniques (Gebicki et al., 2016), either sensorial, involving the “use” of human assessors in the field
82 (Dentoni et al., 2013; Nicell, 2009), or instrumental, such as chemical analyses or electronic noses (Capelli
83 et al., 2014; Szulczyński et al., 2017).

84 In this study we decided to combine odour dispersion modelling and field assessments by human assessors
85 with the technique of the plume inspection (CEN, 2016; Guillot et al., 2012) in order to estimate the odour
86 emissions from a landfill in Southern Italy. The estimation was based on the comparison of the model
87 outputs obtained with different OER values and the registration of odour perceptions around the landfill by
88 a panel of trained assessors. This comparison allowed to evaluate the values for the SOER, which result in a
89 better correspondence between the outcomes of the field inspection and the odour impact simulated by
90 the model during the field inspections.

91 The different SOER values considered for this study are derived basically from two different approaches:
92 the one that considers the odour emissions as independent from the wind speed over the landfill surface,
93 in agreement with the most recent studies on the matter (Lucernoni et al., 2016b), and the one that treats
94 the landfill as a fully passive area source, thereby considering the SOER as a function of the wind speed
95 blowing over the surface. This second approach, although not having any scientific justification, is the one
96 contemplated by the regional guideline on odour emissions in the region where the studied landfill is
97 located. The same problem applies also for other regions in Italy, where the same methodology is foreseen
98 by the local regulations in matter of odour emission control (Regione Lombardia, 2012).

100 2. MATERIALS AND METHODS

101 2.1 Description of the case study

102 The study was conducted at a landfill located in Southern Italy, and more precisely in the Region of Puglia,
 103 close to the city of Taranto. Taranto has an extensive industrial area, comprising a steel plant, an oil
 104 refinery, and the studied landfill, as shown in Figure 1.



105

106 *Figure 1. The city of Taranto and its industrial area comprising a steel plant (red), an oil refinery (blue), and the studied landfill*
 107 *(green)*

108 The proximity of the industrial area to the town north-western boundary is the origin of several odour
 109 complaints, which makes that both people living in this area and local authorities are very attentive to
 110 odour pollution problems.

111 On this background it was decided to carry out a specific study in order to evaluate the odour impact of the
 112 landfill on the surrounding areas.

113 This study has a first objective to apply a “plume method” field inspection in order to determine the
114 presence or absence (yes/no) of recognizable odours coming from the studied landfill, thereby evaluating
115 the plume extent present at the time of the field inspection by identifying the “transition points” from
116 odour absence to odour presence or viceversa (CEN, 2016).

117 After this evaluation, the study has the primary aim to compare the results of the field investigation with
118 the outcomes of a set of atmospheric odour dispersion simulations referred to the periods of execution of
119 the field inspections. This allows to evaluate the SOER values and the hypotheses regarding the SOER
120 constancy or dependency from the wind speed that result in a best fit between simulated odour impact and
121 plume extent determined by field inspection.

122 The reason behind this work is the necessity to experimentally verify the thesis proposed in some recent
123 scientific publications highlighting the different volatilization mechanism regulating emissions from landfill
124 surfaces compared to passive liquid area sources, where forced convection is the driving force for emission.

125 The regional guideline of the Region of Puglia (where the studied landfill is located) indicates the use of
126 wind tunnels for odour sampling on landfill surfaces and the recalculation of the SOER (and thus of the
127 OER) as a function of the wind speed, according to the following relationship, which is valid for passive
128 liquid area sources (Capelli et al., 2009; Capelli et al., 2013b):

129
$$SOER, OER \propto v^{1/2}$$

130 On the contrary, the most recent studies on the matter (Lucernoni et al., 2016b) highlight the need to
131 consider the SOER independent from the wind speed, because of the absence of a direct correlation
132 between wind speed and emission from landfill surfaces (Lucernoni et al., 2017a).

133 **2.2 Field inspection**

134 **2.2.1 The dynamic plume method**

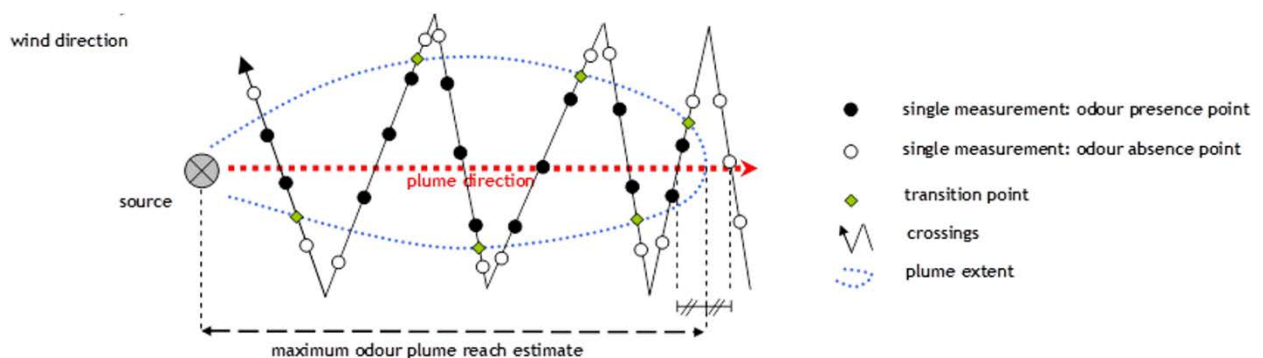
135 Two different types of inspections with human assessors for the determination of odour in the field can be
136 used: the grid (CEN, 2016b) and the plume method (CEN, 2016a). In both cases, human panel members

137 characterize an area by the presence or absence of an odour. Grid method is a long period (one year)
138 statistical survey method to obtain a representative map of a recognizable odour exposure over a selected
139 area, whereas the plume method is a short period experiment (several times of approximately half a day
140 under meteorological conditions) to determine the extent of recognisable odour from a specific source
141 (Capelli et al., 2013c).

142 The plume method, allowing the direct determination of the extent of the downwind odour plume under
143 defined meteorological conditions, which can be compared with the extent of the odour plume obtained by
144 dispersion modelling, is clearly the most appropriate method for the particular scope of this study, i.e. the
145 “backward” estimation of a source emissions.

146 More in detail, we decided to apply the dynamic plume method, whereby the panel members cross the
147 plume following a zigzag direction: by successively entering and exiting the plume the transition between
148 absence and presence of recognizable odour is determined, and thus the extent of the plume is defined
149 (Figure 2).

150 The EN defines that for this type of investigation a minimum number of 2 assessors shall be employed, and
151 that each survey involves the evaluation of a minimum of 20 points, and the determination of at least 6
152 transition points.



153
154 *Figure 2. Schematic diagram of an example of dynamic plume measurement (source EN 16841:2016-2)*

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157 **2.2.1 Design of the field surveys**

158 As already mentioned, for the specific scope of this study, the dynamic plume field inspection method was
159 identified as the most suitable method to “validate” the outputs of the dispersion modelling study and thus
160 go back to the estimation of the landfill effective odour emission rate. However, the normalized method
161 described in the previous paragraph had to be slightly modified and re-adapted to the specific geographical
162 characteristics and logistics of the investigated area.

163 A preliminary inspection survey was organized inside the landfill and in the surrounding areas in order to
164 map the whole investigation area in detail and identify the paths that can be covered by the panel
165 members in order to identify the presence of odours from the landfill.

166 As a first step, the areas surrounding the landfill were inspected thoroughly during a preliminary survey,
167 with the aim of identifying the walkable paths for the panel to be used during the field inspections in order
168 to identify the presence of odours coming from the landfill.

169 Given the big dimensions of the landfill and thus of its surrounding area, in order to design the field
170 inspection surveys properly, it was decided to identify 4 different sub-areas located North, South, East and
171 West of the landfill, respectively, to be inspected depending on the wind direction during the measurement
172 cycles. As an example, if before the start of the field inspection a wind blowing from North to South is
173 registered, then the measurement will take in the sub-area located South of the landfill.

174 The 4 sub-areas were inspected thoroughly by foot and by car, with the aim of tracing paths along which
175 the panel may zig-zag cross the plume, compatibly with the shape of the area to be investigated and the
176 presence of inaccessible areas (e.g., other properties, other plants, railway). This inspection was carried out
177 by using GPS geo-localisation systems in order to transfer the acquired data and trace the paths on
178 common mapping systems such as Google Earth.

179 The identified paths are illustrated in Figure 3, together with the limits of the inaccessible areas.



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Figure 3. Landfill and surrounding paths identified for the field inspection: South (yellow), East (green), North (light blue) and West (red). The black lines indicate the limits of inaccessible areas (private properties or other plants).

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As a general rule, plume inspections shall have a limited duration, in order on one hand to keep a high attention level of the assessors, and on the other hand to avoid that meteorological conditions vary significantly during the inspection. This latter aspect is crucial considering that the aim of the investigation is to evaluate the plume extent, which is clearly highly dependent on the specific meteorological conditions.

187

Because of this requirement about the inspection duration and the high distances involved (as can be derived from the scale in Figure 3 each path is at least 2 km long), the assessors were equipped with bicycles , in order to accelerate the movements along the paths and thus maintain the duration of each inspection within a reasonable interval (i.e. 1.5-2 hours). The possibility to use bikes is mentioned in the EN 16841:2016.

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For similar reasons, the panel was divided into 2 groups, each composed by a minimum of 2 people: this allows to extend each inspection to 2 of the paths indicated in Figure 3, in cases when two paths are downwind. As an example, when the wind blows from South-West to North-East, both the blue (North) and

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195 the green (East) paths will need to be inspected. Those paths are not connected since there is the railway
196 between them, thus making it necessary to have two separated groups inspecting each path.

197 As already mentioned, due to the dependence of the plume extent on the meteorological conditions, it is
198 important that conditions remain stable for the whole duration of the inspection, thus it is necessary to
199 avoid to carry out the field inspections during periods when meteorological conditions are typically
200 unstable, for instance due to thermal inversion, i.e. sunset or sunrise.

201 Since the aim of this study is the evaluation of the most suitable method to characterize odour emissions
202 due to landfill gas emissions through the landfill surface, the surveys were designed as to be conducted in
203 those periods when the only source of odour is landfill gas, and no other interfering sources are present.
204 Considering that the studied landfill is active, this means that the surveys need to be carried out during the
205 times of the day when the fresh waste conferred to the landfill is covered, and thus the emissions from
206 fresh waste tipping is negligible.

207 For this reason, it was decided to carry out the field inspection during the following periods:

- 208 • Early morning, before fresh waste conferring, i.e. between 6.30 am and 8.30 am
- 209 • Afternoon, after covering of the daily conferred waste, but before sunset, i.e. between 5 pm and
210 7.30 pm
- 211 • Night, after sunset, i.e. after 9.30 pm.

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213 **2.2.2 Execution of the field inspection surveys**

214 The field inspection surveys were programmed in the period between Monday, 10th April 2017 and
215 Wednesday, 12th April 2017, involving 6 measurement cycles. The choice to carry out a limited number of
216 measurement cycles is connected to the main objective of the study: in this case the primary aim of the
217 field inspection was not the characterization of the plume extent by itself, but the field inspection was only
218 functional for the evaluation of the most suitable method to estimate odour emissions from a landfill

219 surface, by comparison of the field assessments carried out under specific meteorological conditions with a
 220 simulated odour impact.

221 Each cycle was carried out by 3 experienced assessors, one accompanying person and a measurement
 222 leader, the latter having the function to coordinate the measurement, decide the inspection paths and
 223 conduct the panel along them, and collect the filled measurement forms and the GPS registrations. The
 224 assessors were 3 girls aged between 21 and 27 selected according to the criteria for panel selection
 225 described in the EN 13725:2003 for dynamic olfactometry.

226 As previously mentioned, for each measurement cycle the panel was divided into two groups (one group
 227 composed by one assessor and one accompanying person/coordinator, and the other group by two
 228 assessors and one accompanying person/coordinator, respectively), in order to make it possible to
 229 investigate 2 of the paths indicated in Figure 3 during each measurement cycle.

230 A summary of the measurement cycles, reporting date and hour of the measurement, observed wind
 231 direction and the areas inspected is shown in Table 1. It is worth to mention that the week of the
 232 inspections was characterized mainly by wind calms or by the presence of very weak winds.

Measurement cycle	Date	Time of the day	Landfill activity	Cycle start hour	Cycle end hour	WD (observed)	Groups/ paths
I	10/04/2017	Afternoon	After waste covering	17:00	19:00	SW	Group A - EAST path Group B - NORTH path
II	11/04/2017	Morning	Before waste arrival	7:00	8:30	N	Group A - NORTH path + SW perimeter Group B - WEST path + N perimeter
III	11/04/2017	Afternoon	After waste covering	18:00	19:30	W	Group A - SOUTH + EAST paths Group B - NORTH + EAST paths
IV	12/04/2017	Morning	Before waste arrival	6:30	8:15	NW	Group A - NORTH path + perimeter Group B - NORTH path
V	12/04/2017	Afternoon	After waste covering	17:30	18:40	NE - _	Group A+B - EAST path
VI	12/04/2017	Night	After waste covering	21:45	22:40	N?	Group A+B - Internal + external perimeter

233

234 *Table 1. Summary of the measurement cycles*

235 During each measurement cycle, all assessors and accompanying person/ coordinator were equipped with
 236 a map of the landfill indicating the 4 inspection paths (Figure 3), where they had to indicate the
 237 measurement points, as well as with a GPS system, in order to register their position at any moment of the

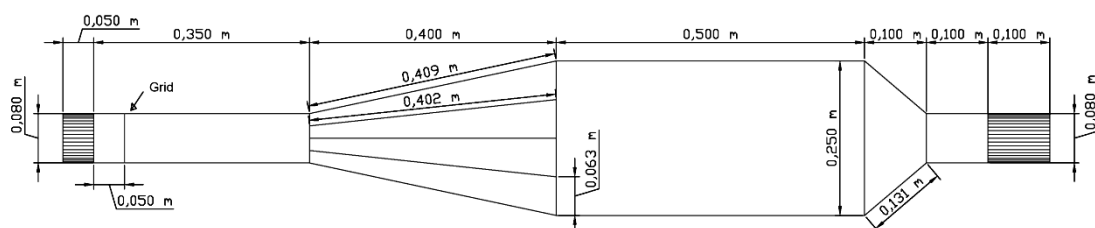
238 measurement cycle. At each measurement point, the assessors were asked to fill in a specific form, in
239 which they had to indicate the presence or absence of odours, and the type of perceived odour.

240 In order to make it possible to recognize the odour of interest for this specific study, i.e. the landfill gas
241 odour, before starting the field inspection survey, the panel members were trained by means of samples of
242 landfill gas odour from the landfill under study at different concentrations.

243

244 2.4 Sampling on the landfill surface

245 In order to allow the comparison of the two main different approaches that can be adopted in order to
246 evaluate odour emissions from landfill surfaces – i.e. the one that considers the odour emissions as
247 independent from the wind speed over the landfill surface, and the one that treats the landfill as a fully
248 passive area source thus considering the SOER as a function of the wind speed over the surface –
249 olfactometric sampling was carried out by using a wind tunnel, which is the sampling method that is
250 typically used for odour sampling on passive area sources contemplated. The wind tunnel used for the
251 study, which is in conformity with the regional guideline on odour emissions in the region of Puglia (where
252 the landfill is located), is the same as described by Capelli et al. (2009). A scheme is shown in Figure 4. A
253 neutral air flow from a synthetic air bottle is flown into the wind tunnel at a flow rate of 2500 l/h.



254

255 *Figure 4. Plant of the wind tunnel*

256 Olfactometric sampling over the landfill surface was carried out simultaneously with the field inspection, in
257 order to make the odour measurements comparable to the field assessments.

258 In the case of wind tunnel measurements, the SOER is then calculated as (Capelli et al., 2013b):

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

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261

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Where SOER is the Specific Odor Emission Rate ($ou_E m^{-2} s^{-1}$), c_{od} the measured odor concentration ($ou_E m^{-3}$), Q_{air} the air flow rate inside the hood ($m^3 s^{-1}$) and A_{base} the base area of the wind tunnel (m^2). The SOER value is the one that can be used as input parameter for dispersion modelling.

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Also other sampling strategies were adopted in order to evaluate the odour emissions from the landfill: the flux chamber and the static hood, according to the procedures described in Lucernoni et al. (2017a). The flux chamber is a “direct method” as the wind tunnel, with the difference that the flux chamber is operated at much lower air flow rates, thus minimizing the dilution effect inside the hood, and thus reducing the risk of emission overestimation (Frechen et al., 2004; Lucernoni et al., 2017a). On the other hand, the “static” hood method is an indirect method for the measurement of the CH_4 emissions from the landfill surface (Lucernoni et al., 2016a; Rachor et al., 2013), in a similar way as provided by the UK “Guidance on monitoring landfill gas surface emissions” (UK Environmental Agency, 2010). 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). Finally, the SOER in $ou_E m^{-2} s^{-1}$ can be obtained by multiplying the LFG specific flow rate by its odour concentration (Lucernoni et al., 2016c; Lucernoni et al., 2017a).

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These two other sampling methods are not discussed further in detail in this paper, since their efficacy for the determination of odour emissions from landfill surfaces has been the object of other previous publications (Lucernoni et al., 2016c; Lucernoni et al., 2017a), and because the main purpose of this paper is to investigate specifically the difference between considering the SOER as a function of the wind speed or as a constant value.

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280

2.4 Odour dispersion modelling

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The dispersion of the odour emissions from the landfill surface was evaluated using the CALPUFF (California Puff Model) model (Scire et al., 2000). CALPUFF is a multilayer, multispecies, non-steady-state, Lagrangian,

283 Gaussian, puff dispersion model. It is able to account for the effects of time and space variations,
284 meteorological conditions (3D met model), on pollutants transport, transformation, and removal (Romeo et
285 al., 2017).

286 The CALPUFF modelling system includes three main components: CALMET, CALPUFF, and CALPOST.
287 CALMET is a meteorological model that develops hourly wind and temperature fields on a 3-D gridded
288 modelling domain. CALPUFF is a transport and dispersion model that CALPUFF that represents a continuous
289 plume as a number of discrete packets of pollutant material and evaluates the contribution of a puff to the
290 concentration at a receptor by a “snapshot” approach. Each puff is “frozen” at particular time intervals
291 (sampling steps). The concentration due to the “frozen” puff at that time is computed (or sampled). The
292 puff is then allowed to move, evolving in size, strength, etc., until the next sampling step. CALPOST is used
293 to process the files from CALPUFF, producing a summary of the simulation results in tabulated forms (de
294 Melo et al., 2012; Wang et al., 2006).

295 The basic equation for the contribution of a puff at a receptor is (Scire et al., 2000; Wang et al., 2006):

$$296 \quad C = \frac{Q}{2\pi\sigma_y\sigma_z} g \exp\left(-\frac{d_a^2}{2\sigma_x^2}\right) \exp\left(-\frac{d_c^2}{2\sigma_y^2}\right)$$

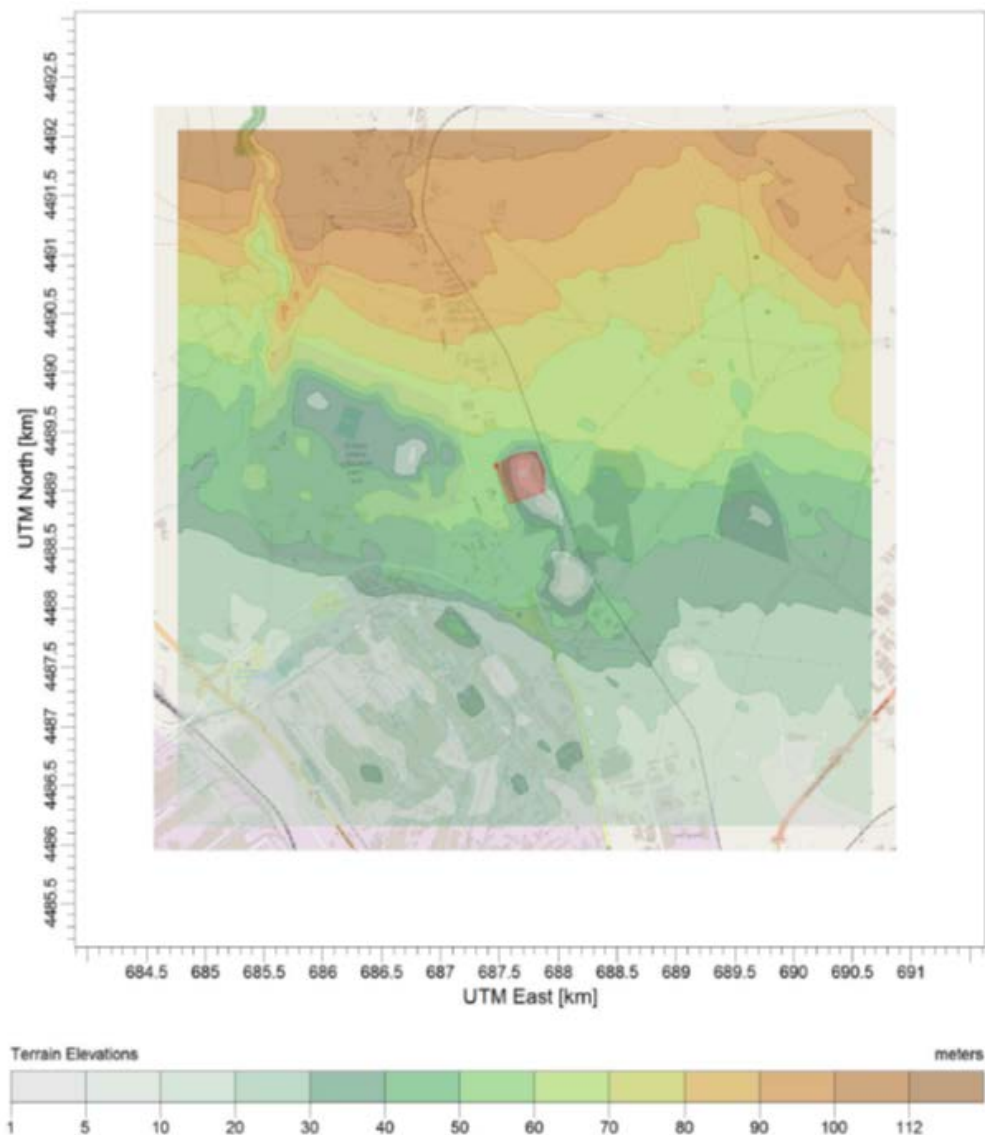
$$297 \quad g = \frac{2}{(2\pi)^{1/2}\sigma_z} \sum_{n=-\infty}^{\infty} \exp[-(H_e + 2nh)^2/(2\sigma_z^2)]$$

298 Where C is the ground level pollutant (i.e. odour) concentration ($\text{ou}_E \text{ m}^{-3}$), Q the product of pollutant (i.e.
299 odour) concentration in the puff and the puff volume (ou_E), σ_x the standard deviation of the Gaussian
300 distribution in the along-wind direction (m), σ_y the standard deviation of the Gaussian distribution in the
301 cross-wind direction (m), σ_z the standard deviation of the Gaussian distribution in the vertical direction (m),
302 d_a the distance from the puff centre to the receptor in the along-wind direction (m), d_c the distance from
303 the puff centre to the receptor in the cross-wind direction (m), g the vertical term of Gaussian equation (m^{-1}),
304 H the effective height above ground of the puff centre (m), and h the mixed-layer height (m).

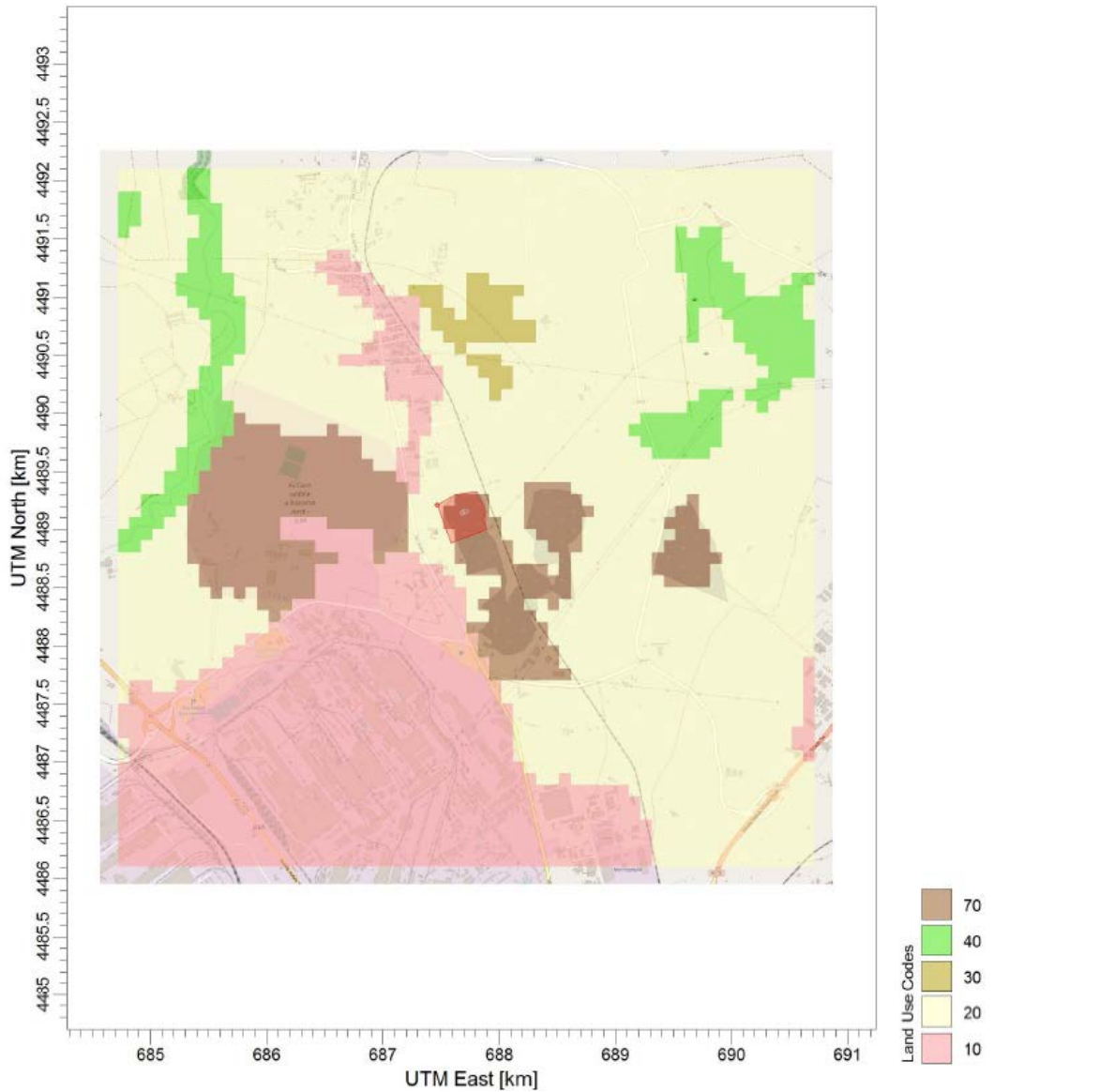
305 The simulation domain comprises an area of 6000 m x 6000 m, with a receptor every 100 m, giving a total
306 of 3600 receptors. The dimensions of the simulation grid were chosen as to include the closest receptors.
307 Terrain elevations and land use of the studied area were considered in the model in order to build the 3D
308 wind field.

309 The meteorological data used for the study are 3D data processed by means of the WRF (Weather Research
310 and Forecasting) model on the studied area relevant to April 2017.

311 The SOER values coming from the sampling campaigns carried out on the landfill surface simultaneously to
312 the field inspection surveys were used as emission data.



313
314 *Figure 5. Terrain elevations of the studied area. The red square indicates the location of the source (landfill area).*



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317 *Figure 6. Land uses considered on the studied area. The red square indicates the location of the source (landfill area).*

318

319 **3. RESULTS**

320 **3.1 Results of the field inspection surveys**

321 The results of the field inspection surveys were processed by combining the information contained in the
 322 forms filled by the assessors with the traces of the paths covered registered by means of the GPS systems.

323 For each measurement cycle, first the significant measurement points were reported on a map (Google
324 Earth), thereby indicating with different colours the points where the presence of recognizable odours
325 coming from the source under investigation (i.e. LFG odour from the landfill) was perceived (red pin), those
326 where the presence of recognizable odours coming from the source under investigation was not perceived
327 (white pin), and those where the recognition of odours was uncertain, meaning that the perceived odour
328 was so weak or sporadic that it was hardly recognizable (yellow colour). As an example, Figure 7 shows the
329 map of the inspection points resulting from the II measurement cycle, carried out in the morning of April,
330 11.



331
332 *Figure 7. Example of map of measurement points resulting from the II measurement cycle*

333 Second, the transition points, corresponding to the limit of the recognizable odour plume under
334 investigation, were identified on the map as the points halfway between the last absence point (white pin)
335 and the first presence point (red pin). Finally, the transition points were connected by means of a
336 interpolation polyline that identifies the plume extent area, i.e. the extent of the area in which the
337 presence of landfill gas odour from the investigated landfill was recognizable by the assessors.

338 As an example, Figure 8 shows the map of the inspection points resulting from the II measurement cycle,
339 carried out in the morning of April, 11, and the corresponding plume extent limits (Figure 9).



340

341 *Figure 8. Example of plume extent limits determined by the connection of the transition points resulting from the II measurement*
342 *cycle*

343 During the nightly measurement cycle (VI cycle), odour perceptions by the assessors were so limited and
344 sporadic, even in proximity of the source (i.e. on the internal perimetral road), that it was not possible to
345 identify a sufficient number of transition points and thus to trace a line corresponding to the limits of the
346 plume extent. This particular situation is also confirmed by the dispersion model run corresponding to this
347 measurement cycle, as will be shown later in this paper (Figure 21).

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349 **3.2 Evaluation of the landfill SOER**

350 Table 2 reports the results of the olfactometric analyses carried out on the samples collected on the landfill
351 surface during the field inspections by means of the wind tunnel (Figure 4).

352 The average odour concentration resulting from the experimental measurement campaigns over the
 353 landfill surface, which is calculated as the geometric mean of the odour concentration values reported in
 354 the last column of Table 2, is $45 \text{ ou}_E \text{ m}^{-3}$. This corresponds to a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$.

355

Date	Sample no.	Description	c_{od} [ou_E/m^3]
10/04/2017	2	Wind I 3	29
10/04/2017	4	Wind I 5	18
10/04/2017	5	Wind I 8	483
10/04/2017	6	Wind I 24	18
11/04/2017	1	Wind H 1	40
11/04/2017	2	Wind H 7	48
11/04/2017	3	Wind H 16	36
11/04/2017	4	Wind H 18	30
11/04/2017	5	Wind I 3	25
11/04/2017	6	Wind I 5	34
11/04/2017	7	Wind I 8	30
11/04/2017	8	Wind I 20	17
11/04/2017	9	Wind I 22	32
11/04/2017	10	Wind I 23	40
11/04/2017	11	Wind I 24	20
12/04/2017	1	Wind H 1	76
12/04/2017	2	Wind H 15	76
12/04/2017	3	Wind H 16	96
12/04/2017	4	Wind H 17	68
12/04/2017	5	Wind H 18	68
12/04/2017	6	Wind I 3	68
12/04/2017	7	Wind I 5	60
12/04/2017	8	Wind I 8	57
12/04/2017	9	Wind I 20	40
12/04/2017	10	Wind I 22	76
12/04/2017	11	Wind I 23	60
12/04/2017	12	Wind I 24	30

356

357 *Table 2. Results of the olfactometric measurements relevant to the samples collected on the landfill surface with the wind tunnel*
 358 *method*

359 In the case of liquid area sources, the SOER shall be considered as a function of the wind speed due to the
 360 mechanism that regulates the emission from the liquid surface to the atmosphere, i.e. forced convection
 361 (Capelli et al., 2009; Lucernoni et al., 2017b). More in detail, the relationship between SOER and wind

362 speed can in most cases be simplified as the SOER being proportional to the square root of the wind speed
363 (Bliss et al., 1995; Capelli et al., 2013b), thus giving:

364
$$SOER_{v_2} = SOER_{v_1} \left(\frac{v_2}{v_1} \right)^{\frac{1}{2}}$$

365 Where v_1 is the air speed during the sampling conditions – in our case corresponding to 0.035 m/s – while
366 v_2 is the wind speed at a specific hour of the simulation time domain (Lucernoni et al., 2017a).
367 Consequently, for odour dispersion modelling purposes, the SOER needs to be re-calculated at the actual
368 wind speed values for every hour of the simulation domain according to this equation.

369 It is important to highlight that the velocity term in the above equation should not be the wind speed that
370 is conventionally measured at 10 m above ground, which would produce a significant over-estimation of
371 the SOER, since the air velocity that produces the volatilization effect from the emitting surface is not the
372 wind speed at 10 m height, but rather the wind speed over the ground, presumably at a height
373 corresponding to the mean surface roughness over the ground (Lucernoni et al., 2017a).

374 Different models can be applied in order to re-calculate the wind speed at different heights. One innovative
375 model sources has been recently developed specifically for liquid area sources by Lucernoni et al. (2017b).
376 However, this model not only is specific for liquids, but it entails the necessity to know the chemical nature
377 of the volatilized compounds, and still requires validation, so it wasn't applied for this study.

378 Instead, it was decided to rely on the more consolidated "Power Law" model, which is obtained empirically
379 starting from a known velocity at certain height, the height corresponding to the desired wind velocity, and
380 a so-called Hellman's parameter (α) that depends on terrain and stability class (Cook, 1997; Lucernoni et al.,
381 2017a):

382
$$v_w^{h1} = v_w^{h2} * \left(\frac{h1}{h2} \right)^{\alpha}$$

383

384

385 **3.3 Comparison of model outputs and field assessments**

386 Once the results of the field inspection surveys were processed as discussed in section 3.1, these were
387 compared with the outputs of the dispersion modelling applied to the odour emissions referred to the
388 same periods of execution of the measurements cycles (Table 1). This comparison was made possible by
389 superimposing the lines defining the limits of the plume extents resulting from each measurement cycle (as
390 the one shown in Figure 8) on the maps resulting from the odour emission dispersion simulations. More in
391 detail, the simulation maps represent the odour concentrations relevant to the simulation period, which
392 coincides with the field inspection measurement cycle period, increased by a “peak-to-mean” factor of 2.3,
393 meaning that the mean values are multiplied by a factor that accounts for peak oscillations around the
394 mean value of concentration over 60 minutes (Schauberger et al., 2012; Sironi et al., 2010), as provided by
395 the regional guideline in matter of odours.

396 As previously discussed, the main objective of this work is to compare two substantially different
397 approaches for the evaluation of odour emissions from landfill surfaces: the first approach treats the
398 landfill as a fully passive area source, thereby considering the SOER as a function of the wind speed blowing
399 over the surface (section 3.3.1), whereas the second approach considers the odour emissions as
400 independent from the wind speed over the landfill surface (section 3.3.2), in agreement with the most
401 recent studies on the matter (Lucernoni et al., 2016b).

402

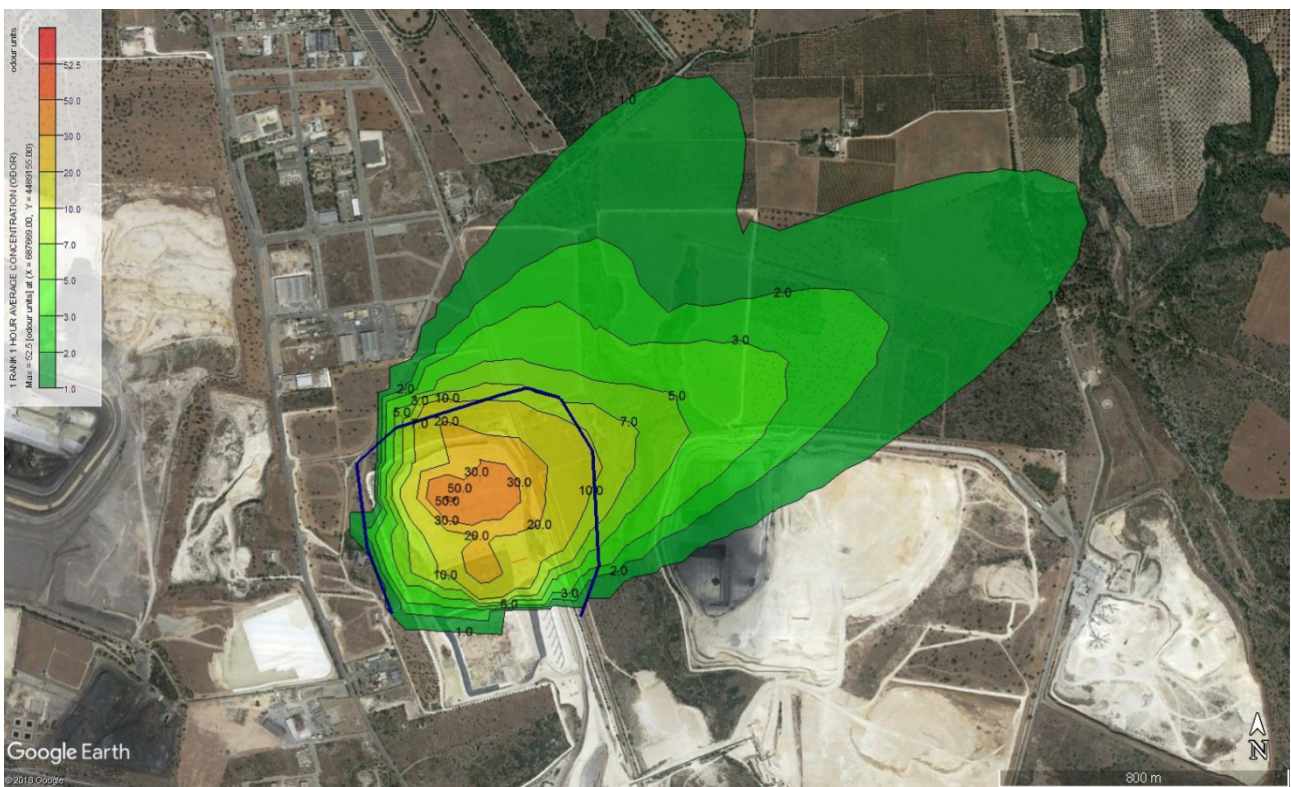
403 **3.3.1 Comparison of field assessments and model outputs considering a variable SOER with the wind** 404 **speed**

405 In order to evaluate the compliance between the odour impact determined experimentally in the field
406 (field inspections) and the odour impact modelled by application of the first approach for the re-calculation
407 of the SOER as a function of the wind speed, Figure 9 - Figure 13 compare the plume extents determined by
408 the 5 field inspection (violet lines), respectively, with the corresponding maps resulting from dispersion

409 modelling obtained for the same period considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ variable with the wind speed
410 (proportional to $v^{1/2}$), according to the “Power Law” described in section 3.3.

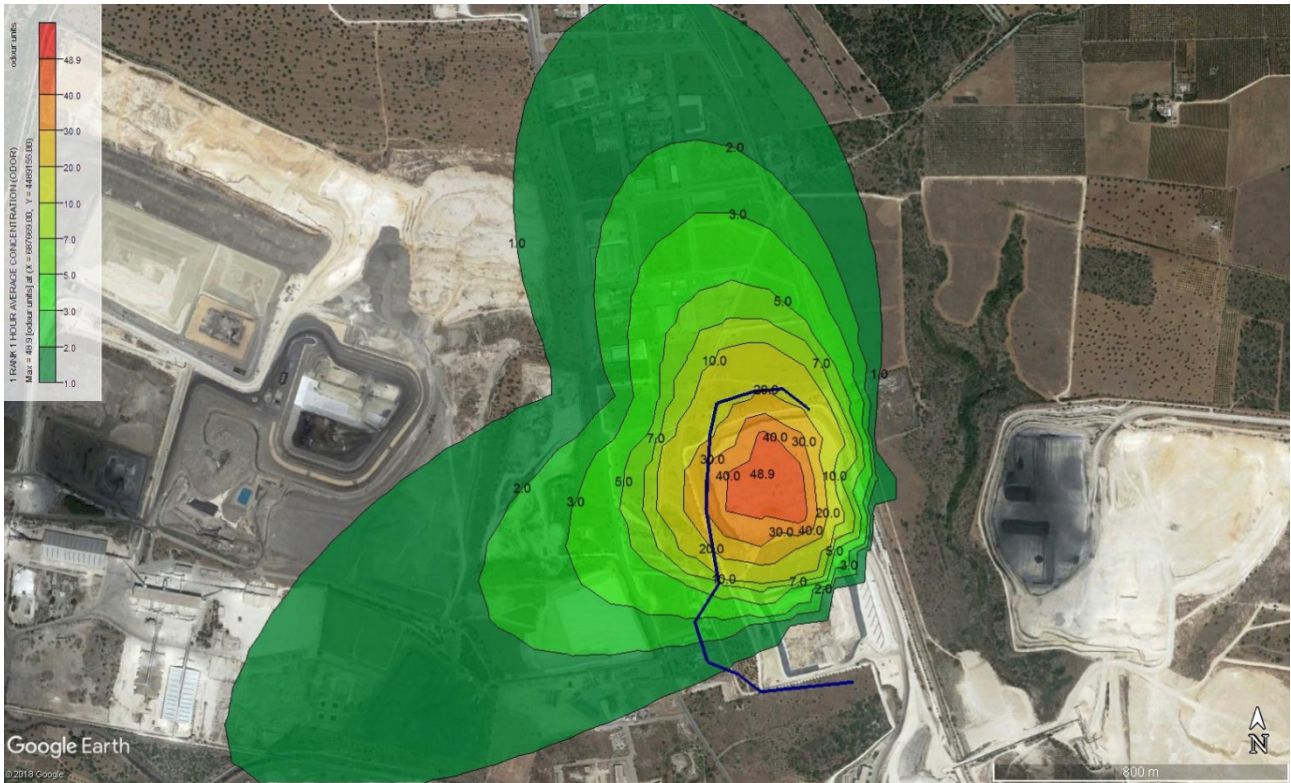
411 The map relevant to the VI measurement cycle is not shown, because odour perception by the assessors
412 was so weak that it was not possible to determine the plume extent, as will be shown in the next section.

413



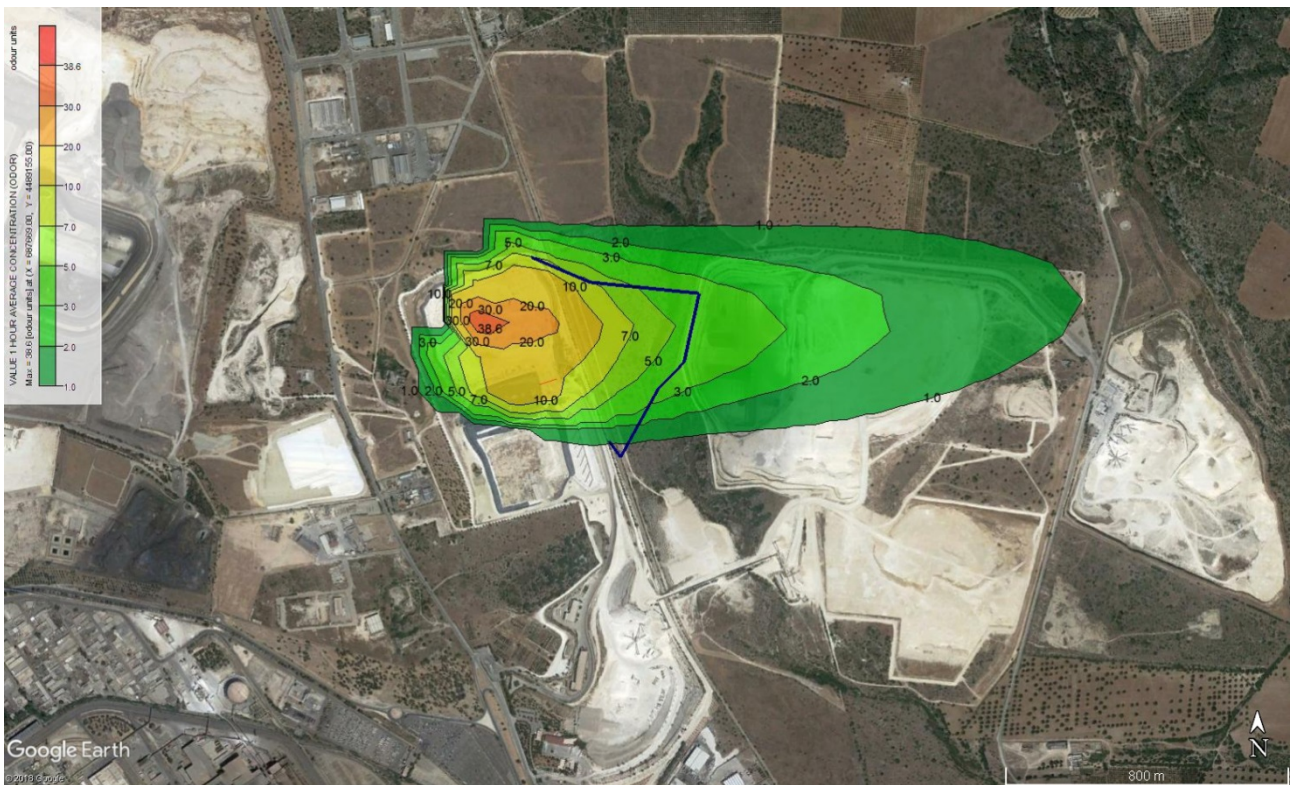
414

415 *Figure 9. Comparison between plume extent determined by field inspection (violet line) and map resulting from dispersion*
416 *modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ variable with the wind speed (proportional to $v^{1/2}$)*



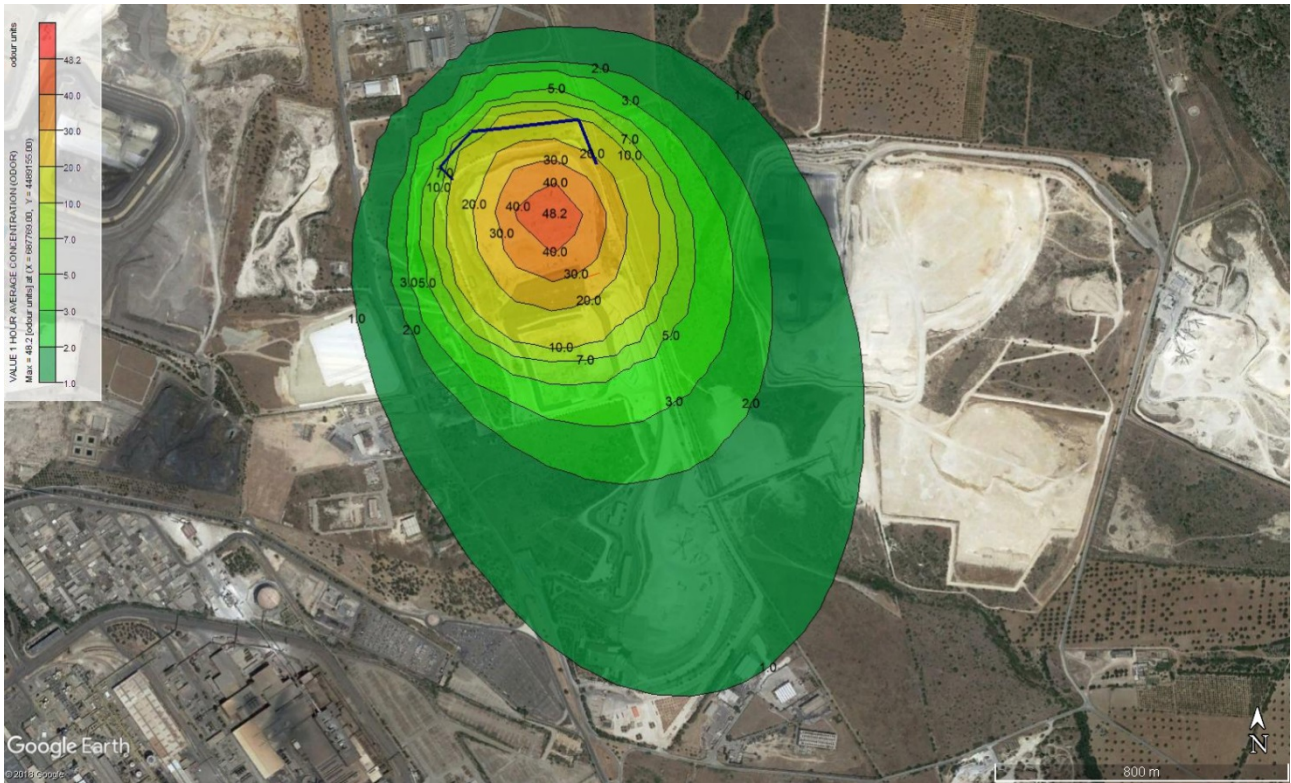
417

418 *Figure 10. Comparison between plume extent determined by II field inspection (violet line) and map resulting from dispersion*
 419 *modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ variable with the wind speed (proportional to $v^{1/2}$)*



420

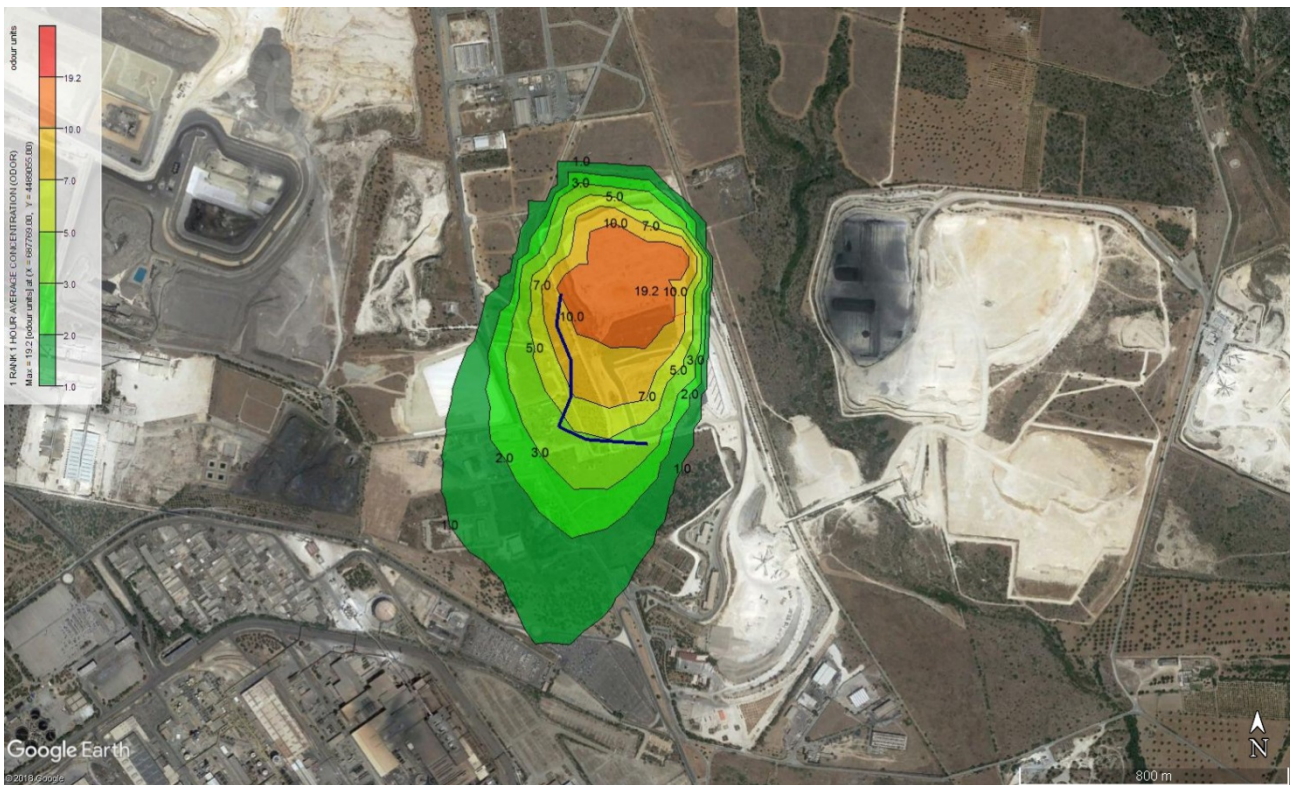
421 *Figure 11. Comparison between plume extent determined by III field inspection (violet line) and map resulting from dispersion*
 422 *modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ variable with the wind speed (proportional to $v^{1/2}$)*



423

424
425

Figure 12. Comparison between plume extent determined by IV field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ variable with the wind speed (proportional to $v^{1/2}$)



426

427
428

Figure 13. Comparison between plume extent determined by V field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ variable with the wind speed (proportional to $v^{1/2}$)

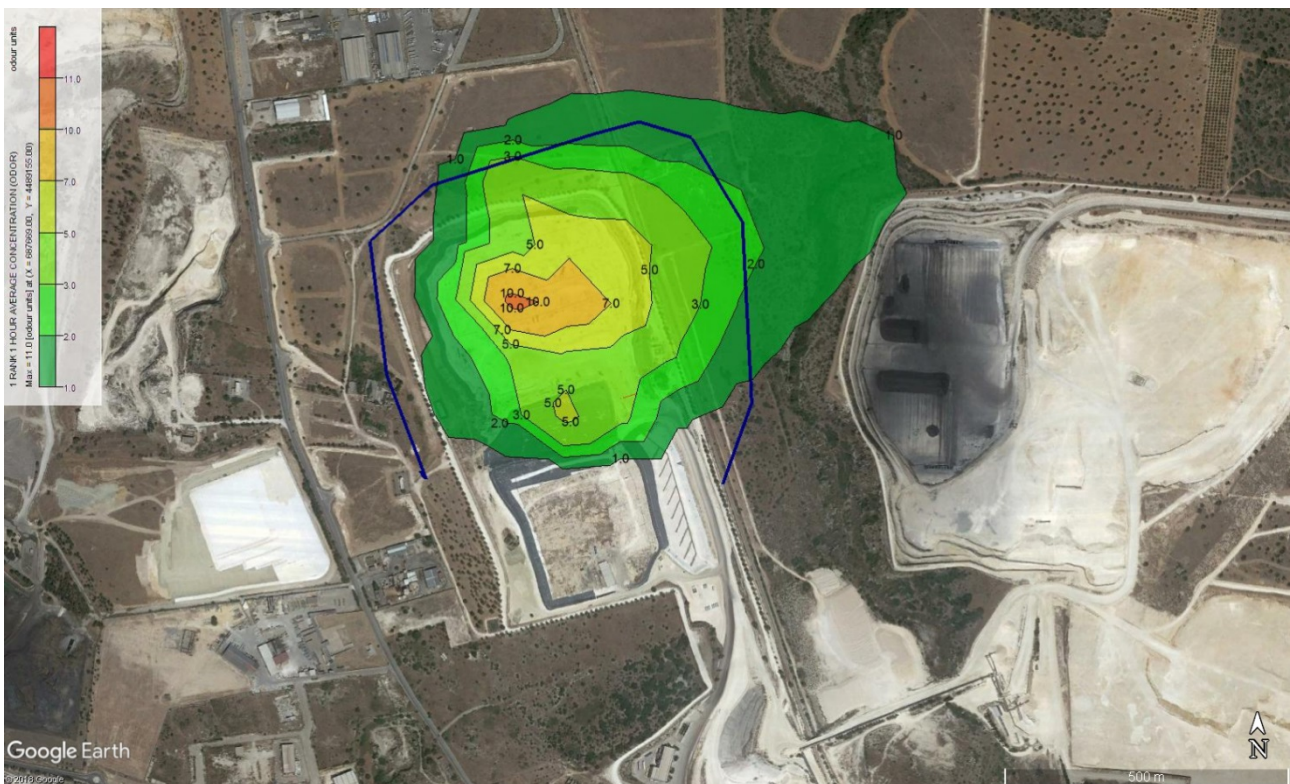
429

430 **3.3.2 Comparison of field assessments and model outputs considering a constant SOER**

431 A similar comparison was done in order to evaluate the agreement between experimentally determined
432 odour impact and the odour impact modelled by application of the second approach that considers the
433 SOER as a constant with the wind speed, thus using a constant SOER value of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ as obtained
434 from the wind tunnel measurements on field.

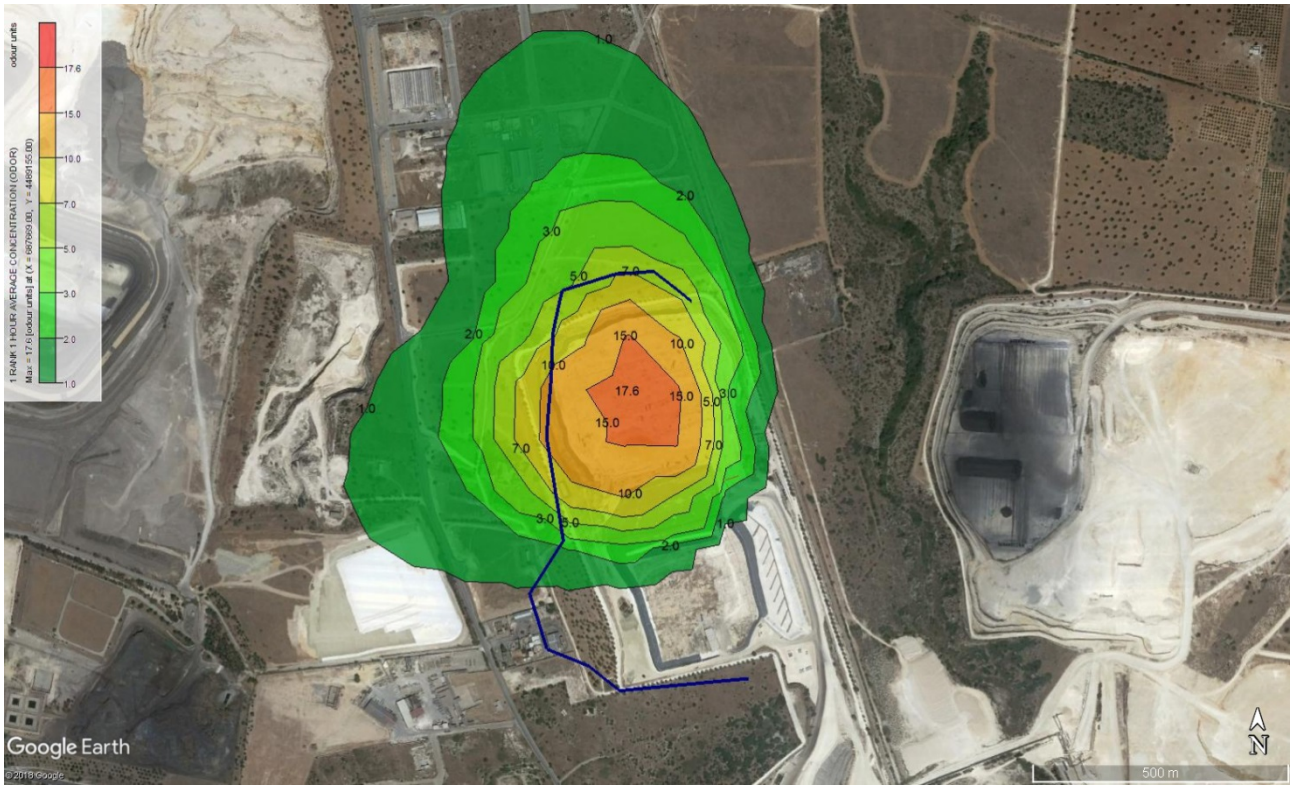
435 Therefore, Figure 14 - Figure 18 show the comparison maps with the plume extents determined by the 5
436 field inspections (violet lines, same as in Figure 9 - Figure 13), respectively, superimposed to the maps
437 obtained from application of the dispersion model for the same period by choosing a constant SOER value
438 of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$.

439 All the comparisons between field assessments and model outputs are dependent on the specific model
440 settings and conditions: one important modelling condition that should be considered in order to evaluate
441 the correspondence between model outputs and the odour impact assessed in the field, is the use of a
442 constant peak-to-mean factor of 2.3, as will be discussed in the following section.



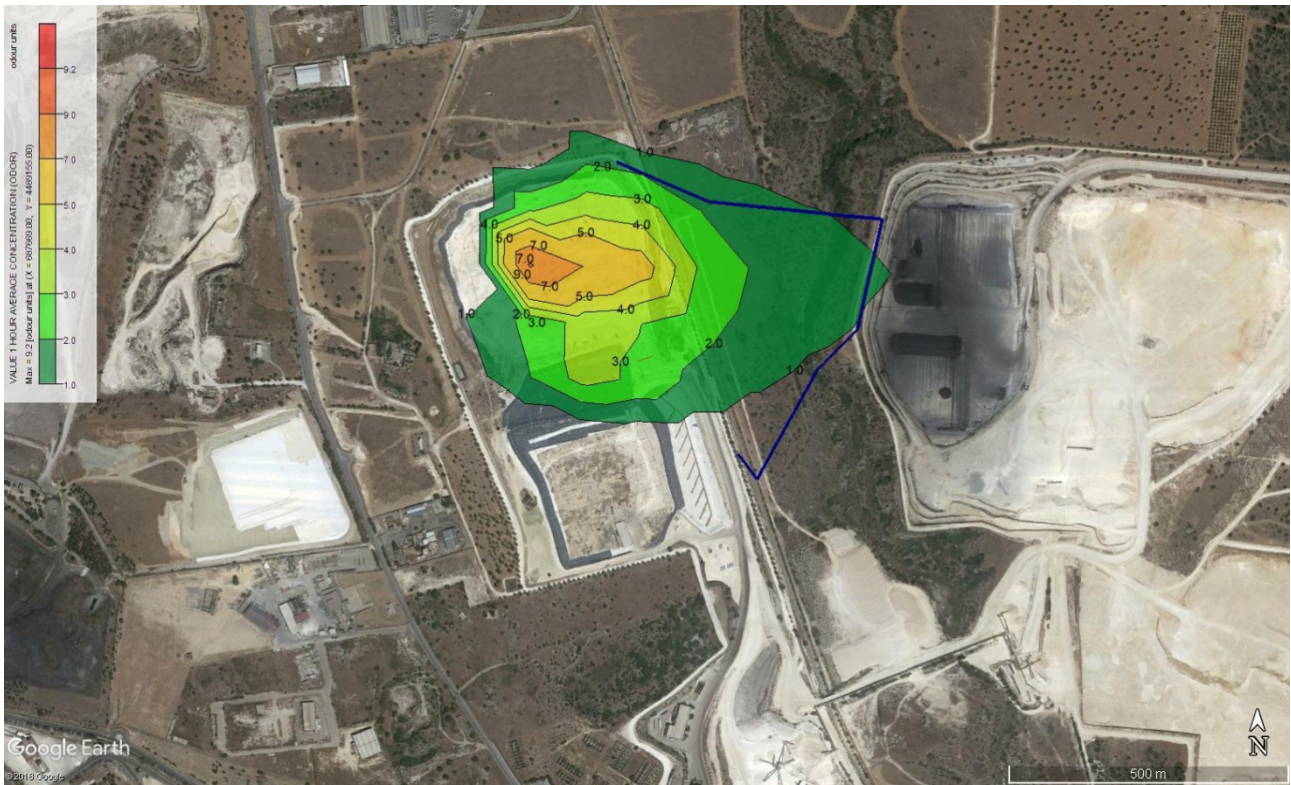
443
444 *Figure 14. Comparison between plume extent determined by field inspection (violet line) and map resulting from dispersion*
445 *modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed*

446



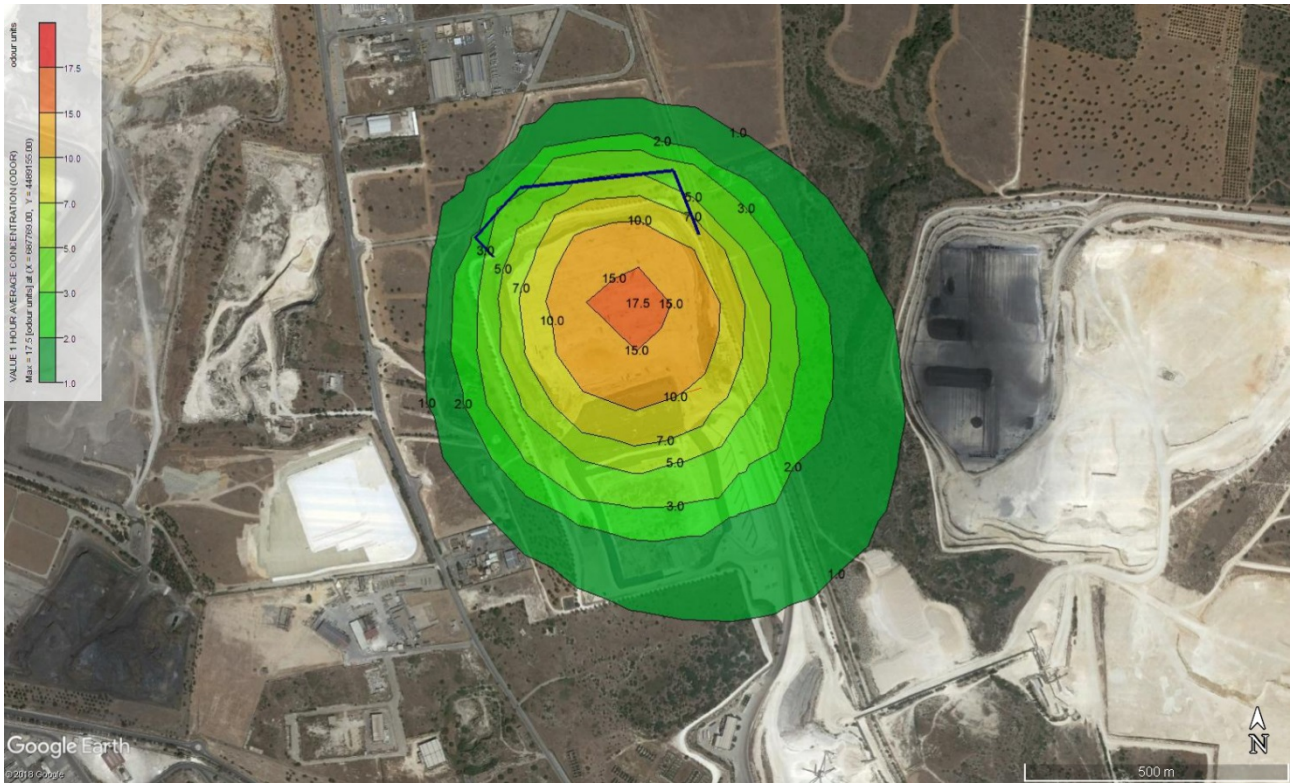
447

448 *Figure 15. Comparison between plume extent determined by II field inspection (violet line) and map resulting from dispersion*
449 *modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed*



450

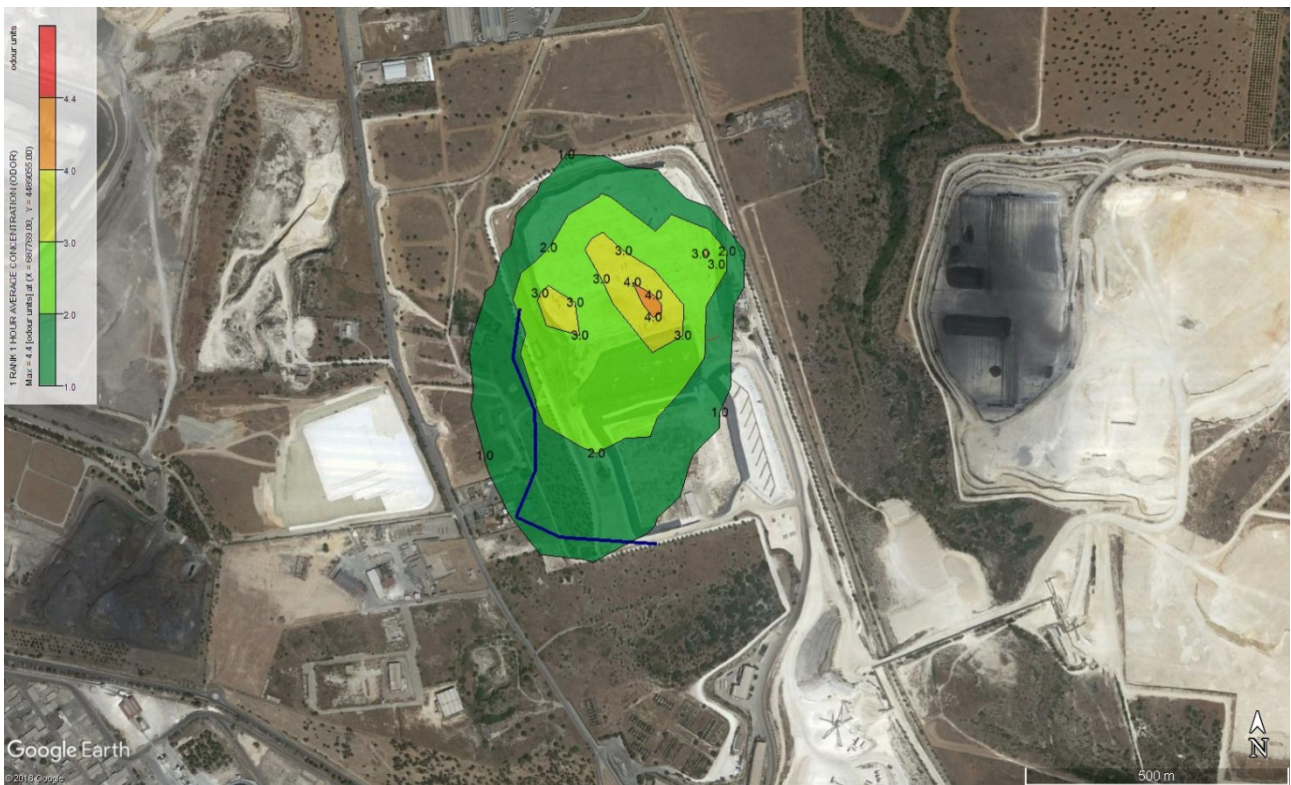
451 *Figure 16. Comparison between plume extent determined by III field inspection (violet line) and map resulting from dispersion*
452 *modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed*



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Figure 17. Comparison between plume extent determined by IV field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed



456

457
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Figure 18. Comparison between plume extent determined by V field inspection (violet line) and map resulting from dispersion modelling obtained considering a SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed

459

460 4. DISCUSSION

461 4.1 Evaluation of the comparison of model outputs and field assessments

462 Based on the comparison of the field assessments and the model outputs obtained by considering the
463 landfill SOER as a function of the wind speed (Figure 9 - Figure 13), it is evident that this approach
464 significantly overestimates the landfill odour emissions. In Figure 9 - Figure 13 it is clearly visible that the
465 simulated odour impact results in odour concentrations that are almost one order of magnitude higher
466 than those determined in the field by a panel of trained and expert assessors.

467 On the contrary, the comparison of the model simulations based on a constant SOER, independent from
468 the wind speed (Figure 14 - Figure 18) shows a better correspondence between model outputs and field
469 assessments, in terms of shape and extension of the determined odour plume extents.

470 In order to optimize the correspondence between a further step was made: considering that the odour
471 concentration at which the assessors are able to recognize the presence of odours in the field corresponds
472 to the so called "odour recognition threshold", which lies around 2-3 $\text{ou}_E \text{ m}^{-3}$ (Dentoni et al., 2013), the
473 SOER value used as input parameter for the dispersion model was varied from the value of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$
474 obtained from the wind tunnel measurements on field as to best fit the field inspection results.

475 According to this procedure, the SOER value that results in a best correspondence between model outputs
476 and odour impact determined during the field measurement cycles I, III and V (Figure 14, Figure 16 and
477 Figure 18, respectively) wasn't varied: with a constant SOER of to $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ a very good fit is already
478 obtained, resulting in a plume extent determined by the field inspection very close to the modelled iso-
479 concentration lines corresponding to 2-3 $\text{ou}_E \text{ m}^{-3}$.

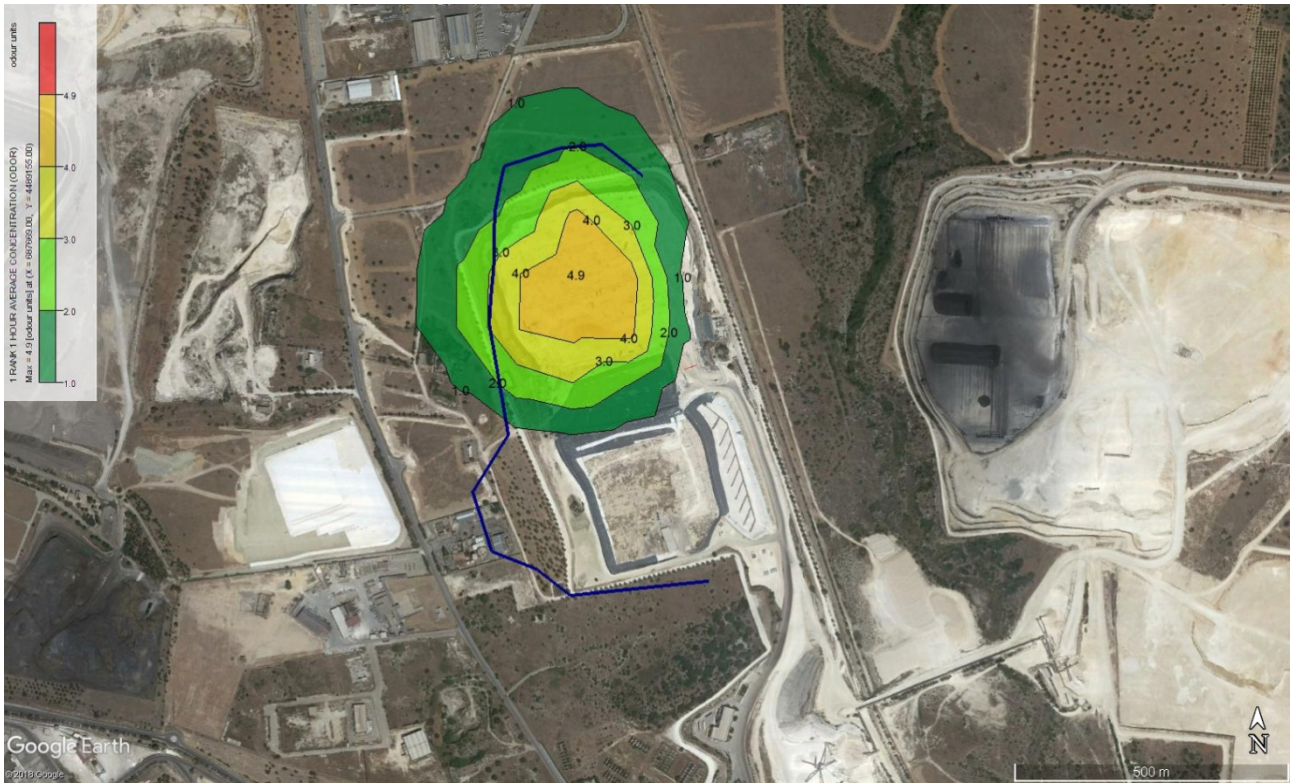
480 Instead, as can be seen from Figure 15 and Figure 17, the use of a constant SOER of to $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$
481 results in a slight overestimation of the modelled odour impact, since the lines delimiting the plume extents
482 determined by field inspection fall over the iso-concentration lines corresponding to odour concentrations
483 of about 5-7 $\text{ou}_E \text{ m}^{-3}$. For this reason, the SOER values used for dispersion modelling had to be reduced to
484 0.07 and $0.1 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$, respectively, in order to obtain a "best fit" (Figure 19 and Figure 20).

485 Also the “best fit” SOER values are referred to the specific model settings and conditions, i.e. in this specific
486 case, the use of a constant peak-to-mean factor of 2.3. The effect of the peak-to mean factor on the
487 comparisons between field assessments and model outputs will be discussed in the following section.

488 Another reason why the SOER value of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ determined based on the WT measurements over
489 the landfill surface (section 3.2) is possibly overestimated can be explained looking at the olfactometric
490 measurement results reported in Table 2. Indeed, the SOER value of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ comes from the
491 average odour concentration of $45 \text{ ou}_E \text{ m}^{-3}$ calculated from the odour concentration values reported in
492 Table 2. In general, the odour concentration values measured in the samples collected with the WT over
493 the landfill surface are so low that they are likely to be not representative exclusively of the characteristic
494 odour of the LFG emitted through the landfill surface, but it is likely that at least a share of the sample
495 concentration value is given by the so-called background odour. In this situation, the background odour is
496 intended as the odour of the landfill surface itself and of its components (e.g. soil, grass, sand...), odour that
497 contributes to the overall concentration value of the collected sample, but is not representative solely of
498 the emitted LFG odour. There are literature references identifying typical background odour concentrations
499 from 5 to $60 \text{ ou}_E/\text{m}^3$ (UK Defra, 2010) or the intrinsic lower detection limit for Dynamic Olfactometry as 20-
500 $50 \text{ ou}_E/\text{m}^3$ (Capelli et al. 2013a).

501 This is why the application of this direct approach by means of WT for the evaluation of the OER from
502 sources that are not highly odorous such as landfill surfaces may result in an overestimation of the real
503 emissions and the real impact (Lucernoni et al., 2016c).

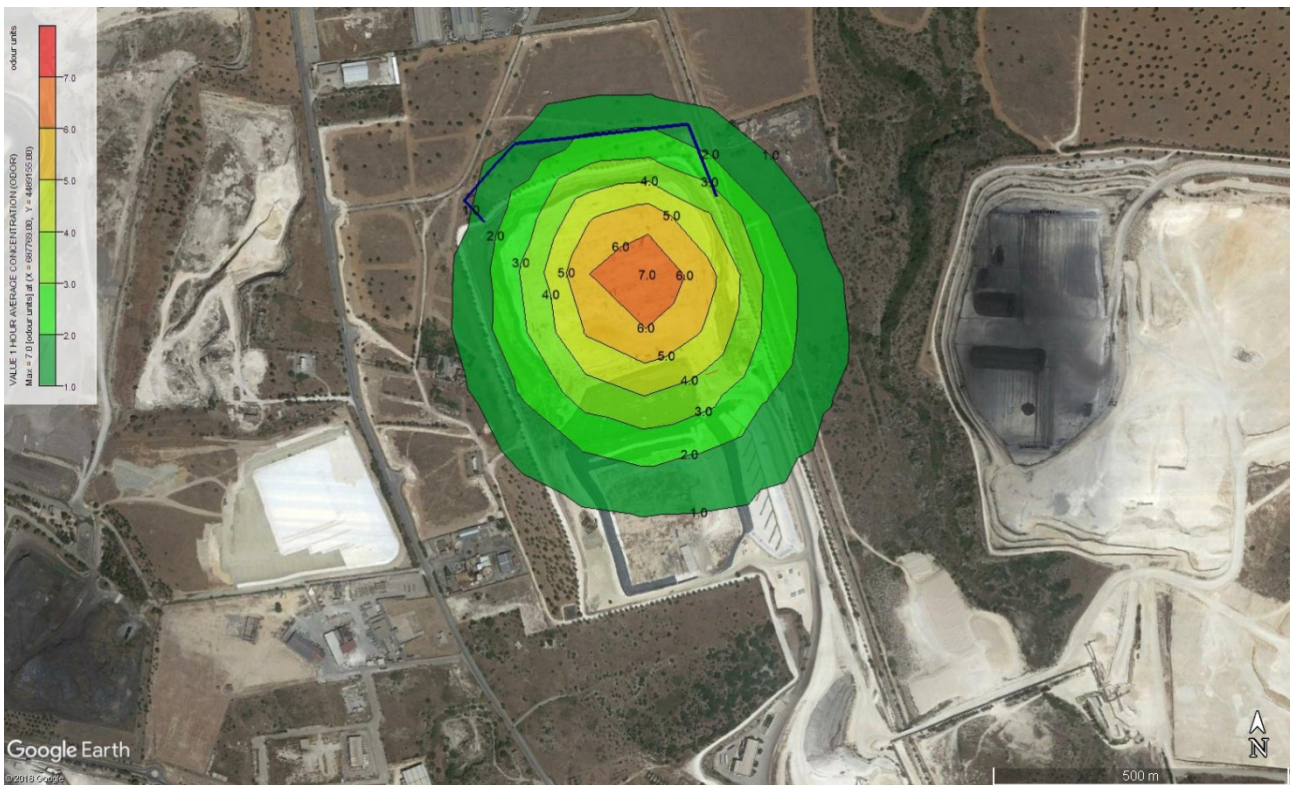
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Figure 19. Comparison between plume extent determined by II field inspection (violet line) and "best-fit" map resulting from dispersion modelling obtained considering a SOER of $0.07 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed



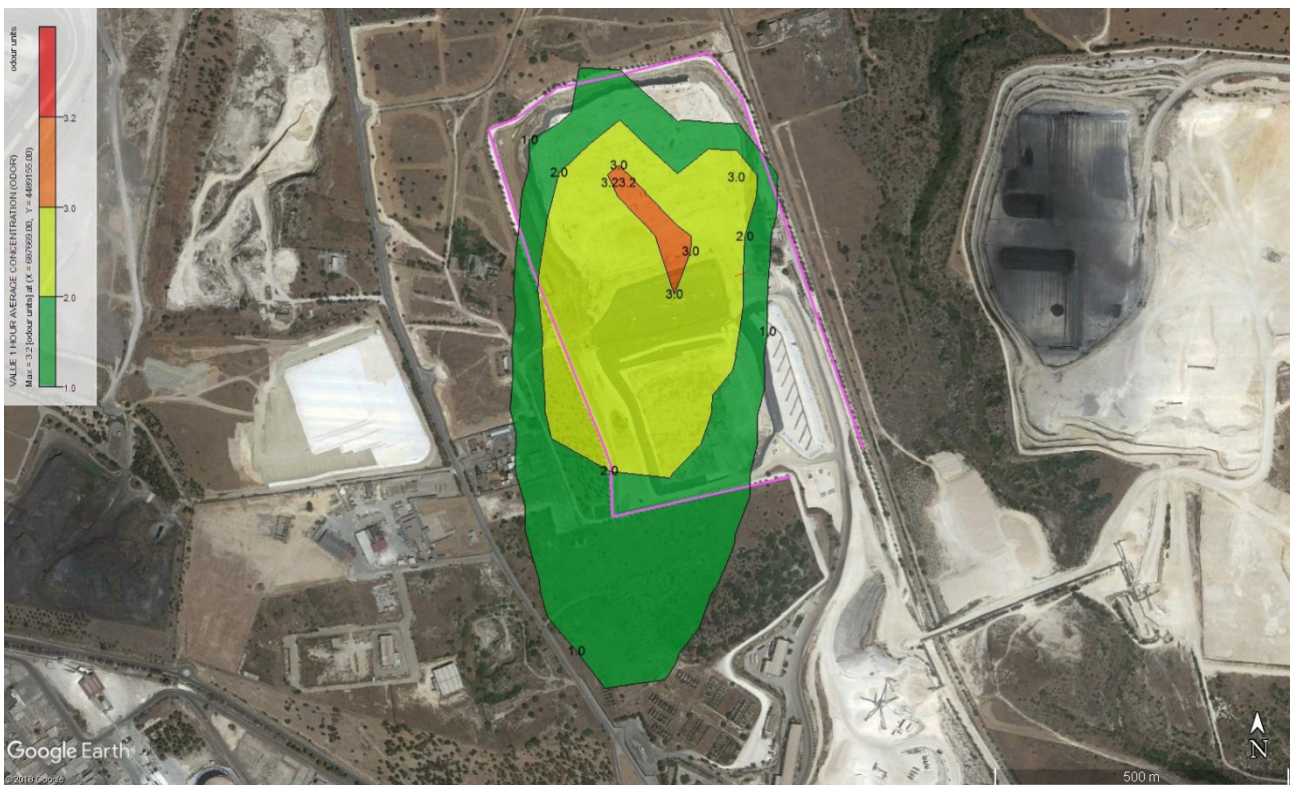
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Figure 20. Comparison between plume extent determined by IV field inspection (violet line) and "best-fit" map resulting from dispersion modelling obtained considering a SOER of $0.1 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ constant with the wind speed

511

512 Another interesting element for the comparison between field assessments and model outputs is the result
513 of the dispersion model run referred to the VI measurement cycle, during which the assessors weren't able
514 to recognize the presence of odours coming from the landfill on the inspected paths. The map resulting
515 from dispersion modelling obtained by considering a constant SOER of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ is shown in Figure
516 21. The pink line indicated in Figure 21 represents the internal perimetral street of the landfill, which is the
517 closest path to the emission source that could be inspected by the assessors. It is clearly visible that in
518 correspondence of this path, the modelled odour concentration is mostly below $1 \text{ ou}_E \text{ m}^{-3}$; only in a small
519 portion of the path the iso-concentration line corresponding to $2 \text{ ou}_E \text{ m}^{-3}$, which is the lower limit of the
520 odour recognition threshold, is crossed. If the previous considerations about the possibility that the SOER
521 of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$ might be overestimated, the failed odour perception by the assessors in the field appears
522 justified by a particular situation in which the odour emissions from the landfill were hardly perceivable
523 even at a low distance from the source, as proven by the model.



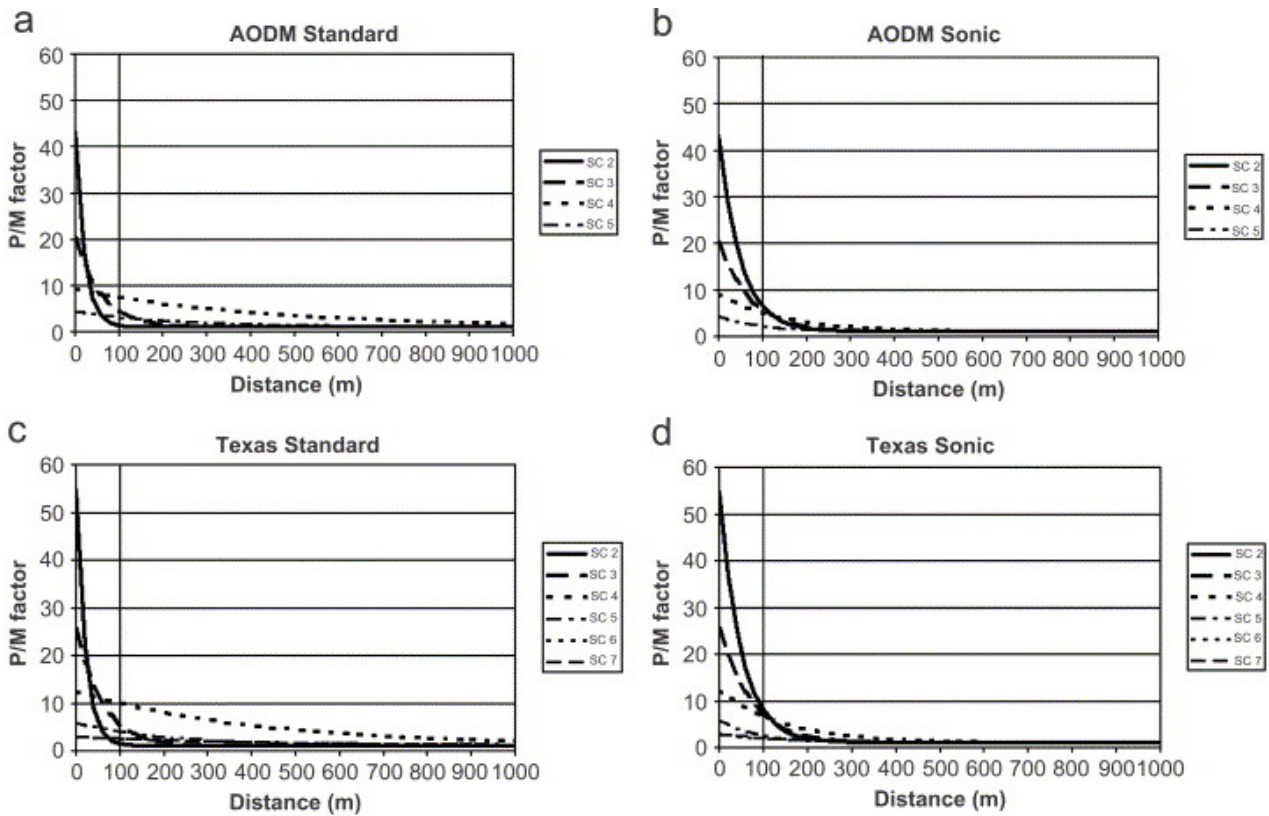
524
525 *Figure 21. Map resulting from dispersion modelling relevant to the VI field measurement cycle obtained considering a constant SOER*
526 *of $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$. The pink line indicates the internal perimetral street of the landfill.*

527

528 **4.2 Influence of the peak-to-mean factor**

529 In order to perceive an odour, it is sufficient that its odour concentration exceeds the detection threshold
530 for the duration of a breath (about 3.6 seconds). Odour concentration, as well as any other atmospheric
531 scalar variable, is subject to instantaneous fluctuations due to turbulence. Given that the adopted model
532 calculates the hourly mean odour concentration value, it is necessary to deduce the peak odour
533 concentration, defined as the concentration that in one hour is exceeded with a probability of 10^{-3} , i.e. for
534 over 3.6 seconds. The peak odour concentration can be obtained by multiplying the hourly mean odour
535 concentration by a by a coefficient called peak-to-mean factor (Schauberger et al., 2000; Capelli et al.,
536 2011). Some recent scientific studies discuss the opportunity to consider a variable peak-to-mean factor,
537 evaluated as a function of the distance from the source and the stability class (Schauberger et al., 2000;
538 Schauberger et al., 2012). More in detail, some studies (Piringer et al., 2007) prove that, at close distance
539 from the source (< 100 m), and with unstable atmospheric conditions, the peak-to mean factor can reach
540 values of 50, which then rapidly decreases with the distance as to reach a value of 1 at about 1000 m from
541 the source (Figure 20).

542 Despite these experimental evidences, in this study, a constant peak-to-mean factor was adopted in
543 accordance with the regional guidelines in matter of odour.



544

545 *Figure 22. Peak-to-mean factors as a function of the distance from the source and the stability class (from Piringier et al., 2007)*

546

547 It is important to highlight that, for all field measurement cycles, the presence of odour from the landfill
 548 was detected only in proximity of the source (significantly below 1000 m).

549 Therefore, all the above comparisons between model outputs and field inspections (Figure 9 - Figure 20)
 550 are conducted at very close distance from the source (few tenths/ hundreds of meters). In these conditions,
 551 the considerations about the dependence of the peak-to-mean factor from the distance from the source
 552 become significant. Based on the graphs shown in Figure 22, it appears clearly that at such distances higher
 553 peak-to-mean factors than the value of 2.3 suggested by the regional guideline should be used (probably in
 554 a range of 5-10).

555 If this hold true, then the “best fit” SOER values evaluated in order to maximize the correspondence
 556 between model outputs and field inspections as described in section 4.1 would result further reduced,
 557 probably approaching values in the order of $0.05 - 0.1 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$.

558

559 **5. CONCLUSIONS**

560 This study has the specific aim of evaluating the most suitable method to estimate odour emissions from a
561 landfill surface, thereby counterposing two substantially different approaches: the one that treats the
562 landfill as a fully passive area source, thereby considering the SOER as a function of the wind speed blowing
563 over the surface, and the one that considers the odour emissions as independent from the wind speed over
564 the landfill surface, in agreement with the most recent studies on the matter.

565 The comparison of the field assessments and the model outputs obtained by considering the landfill SOER
566 as a function of the wind speed clearly highlights that this approach significantly overestimates the landfill
567 odour emissions.

568 This overestimation is even more emphasized considering the discussion about the peak-to-mean factor
569 reported in the previous section (4.2), which points out that the peak-to-mean factor adopted for the
570 evaluation of the peak odour concentrations should be increased, presumably by a factor 2.

571 On the contrary, the comparison of the model simulations based on a constant SOER, independent from
572 the wind speed results in a good correspondence between model outputs and field assessments, both in
573 terms of shape and extension of the determined odour plume extents. Correspondence between simulated
574 and experimentally assessed plume extents is optimized for constant SOER values comprised between 0.07
575 and $0.25 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$. As previously mentioned, considering that the peak-to-mean factor of 2.3 used for the
576 simulations is likely to be underestimated, an even better fit would be expected for constant SOER values in
577 the order of $0.05 - 0.1 \text{ ou}_E \text{ m}^{-2} \text{ s}^{-1}$.

578 In conclusion, this study proves that landfill surfaces cannot be considered as equivalent to fully passive
579 area source, since the main driving force for volatilization of odours into the atmosphere is not forced
580 convection, as already discussed in previous recent research work on this subject. As a general rule, odour
581 emissions from this particular kind of source should be considered as independent from the wind speed
582 (i.e. constant). Moreover, the opportunity to use alternative methods instead of WT, which generally tend

583 to overestimate emissions from low-emissive odour sources such as landfill surfaces, can also be
584 considered for this purpose, as has been proposed in other works (Lucernoni et al., 2016c; 2017a).

585

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589

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