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Assessment of the Odour Quality of the Air Surrounding a Landfill Site: A Case Study

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Citation: Szałata, Ł.; Zwoździak, J.; Majerník, M.; Cierniak-Emerych, A.; Jarossová, M.A.; Dziuba, S.; Knošková, Ľ.; Drábik, P. Assessment of the Odour Quality of the Air Surrounding a Landfill Site: A Case Study. *Sustainability* **2021**, *13*, 1713. https://doi.org/10.3390/su13041713

Academic Editor: Vincenzo Torretta
Received: 24 November 2020
Accepted: 1 February 2021
Published: 5 February 2021

Abstract: In the present study, the authors assessed the odour quality of the air in the vicinity of a landfill site using a case study of a waste management plant that processes non-hazardous and inert waste as an example. An analysis of the impact of the facility under study on the odour quality of the air was performed based on a mathematical modelling system used to, among other things, assess the impact of investments in air quality both in Poland and worldwide. The most important element of the system is the puff dispersion model CALPUFF. In conclusion, the analysis of the plant's odour impact clearly indicates a significant impact on the air quality in the studied area. The range of the impact may even reach up to 1.5 km; in the nearest locality, the odour perceptibility threshold may be exceeded for more than 3% of the hours in a year. However, taking into account the fact that the landfill is located within an agricultural area, the incidental odour impact in this area may also be associated with periods of intensive fertilization and a roadside ditch collecting municipal sewage from roadside households.

Keywords: odours; municipal waste management; puff dispersion modelling

1. Introduction

The research problems addressed in the present study, which concerns air quality assessment and business entities' impact—including that of the waste management sector—on their surrounding environments in terms of odour nuisance, are important and topical issues from the point of view of further shaping current economic, environmental, and social resources. The odours emitted from landfills may cause temporary symptoms, such as nausea and headaches. People with respiratory ailments (e.g., asthma) can be especially sensitive to the odorous compounds emitted from landfills [1]. In recent years, regulatory efforts have been directed towards the characterisation of volatile organic compounds (VOCs) originating from solid waste facilities due to their impacts on air quality and human health (i.e., psychological stress, irritation, toxic reactions) [2,3]. Among the existing types of industrial installations that can cause odour nuisances, landfills represent one of the most common sources of odour emissions and complaints [4]. The clear need for precision in obtaining reliable scientific estimates in this area has led to the development of the research topics analysed here.

At present, there are many municipal waste management facilities operating in Poland and abroad whose locations often lead to a deterioration in the comfort of those living in the surrounding communities due to the housing being often closely located in addition to the specificities of municipal waste processing and disposal, which provoke social discussions about their operation [5]. These issues are so topical that the unpleasant odours that occur around sources of air pollution lead to numerous complaints about environmental quality. Sources of odour emissions in the waste management sector are very common [6]. One of the main sources of odour nuisances in this sector involves its basic activities, such as:

- Waste storage;
- Waste sorting;
- Biological waste treatment.

The literature review, the authors' own research, and the results obtained in this study have led to the conclusion that municipal facilities are an important potential source of odours, as supported by the shared fairly common opinion on this issue among many environmental protection authorities and the segment of society that actively responds to such problems [7–11]. In a recent landfill odour study, among the 68 odorous gases identified (inorganic compounds, halogenated compounds, aromatics, volatile fatty acids (VFAs) aldehydes, ketones, esters, hydrocarbon, and other sulphur and nitrogen compounds), NH_3 and H_2S accounted for over 90% and 5% of the total odorous gas concentrations, respectively [12]. Moreover, odours are dynamically changing compounds, the detection of which requires very advanced analytical methods.

Therefore, the authors attempted to determine and systematise the current impact related to the operation of landfills by taking land development and methods for determining the level of odour impact due to the operation of a plant/installation into account. The air quality in the surroundings of municipal landfills and mechanical and biological treatment plants is currently a constantly controlled component of the environment regulated by both national and international law [13]. Representatives of landfill sites in Poland declare that there is low odour nuisance for the surrounding environment (50%) or no odour impact (48%) [7]. For 42% of the landfills, a higher intensity of odour impact in the areas of the sites was observed. However, the maximum radius of odour impact was assessed individually for each landfill site by taking into account the conditions of its surroundings and using advanced modelling tools. The main atmospheric factor influencing odour nuisance was air temperature (68%) followed by wind speed and direction (24%) [7]. The results of inventory studies of landfills in Poland in terms of the basic sources of odour nuisance and factors affecting this nuisance clearly indicate that the main source is landfilling (42%) [7]. With respect to the addressed problem and its proposed solutions, the added value that can be obtained as a result of clarification of the possible environmental effects associated with the operation of the landfill provides the opportunity to make optimal decisions in social debates at the spatial planning stage [14]. Furthermore, a complete sample analysis of odours related to these types of objects can be applied with respect to the problems that appear and their resolutions. Based on an example, the above issue was analysed in detail by taking into account the environmental research carried out in relation to the actual local conditions.

2. Material and Methods

2.1. Analytical Method

An analysis of the impact of the studied facility on the odour quality of the air was performed based on a mathematical modelling system used to, among other things, assess the impact of investments in air quality both in Poland and worldwide. Methods for detecting malodourous compounds over a large area can be divided into the following main types:

- Analytical—analysis of the kinetics of chemical transformation processes of odours;

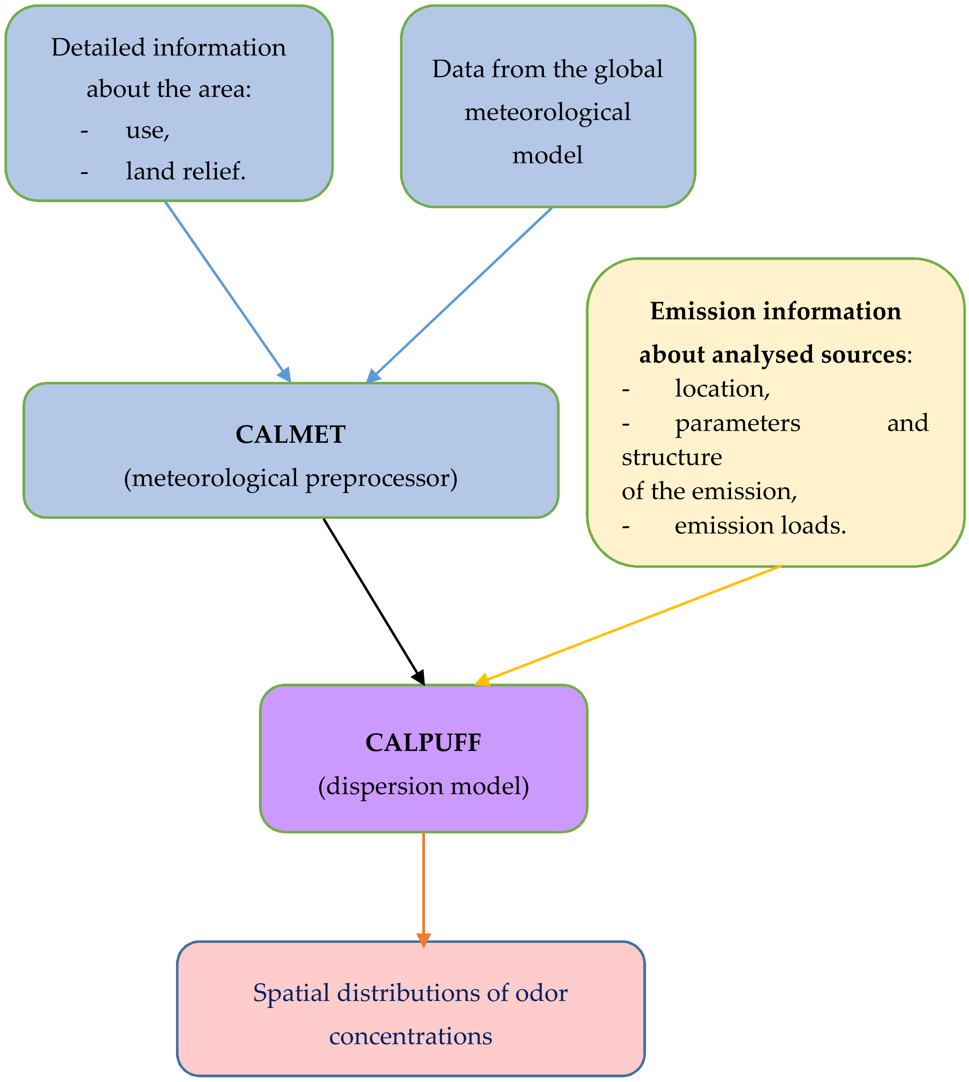
- Sensory—environmental research or dynamic olfactometry;
- Sensor—instrumental–electronic noses.

Electronic noses (ENs) are now widely employed in different fields, such as the automotive, environmental monitoring, medical diagnostic, and food processing fields [15]; an example is the Arduino e-nose [16].

Analysis of the kinetics of the chemical transformation processes of odours is a basic analytical method used for theoretical estimation of the levels of odour concentrations that may arise as a result of chemical reactions. On the other hand, sensor-based environmental research provides the most precise assessments based on actual environmental conditions. A sensory method was chosen as the method for estimating the odour level; it was based on actual tests carried out in accordance with EN 13725. The adopted modelling method was used in conjunction with a sensory detection method, which allowed us to obtain reliable results.

Analysis of the impact of an object on the odour quality of air was performed on the basis of a mathematical modelling system that is used to, inter alia, assess the impact of investments in air quality in Poland as well as in the rest of the world. This system is also equipped with a calculation module dedicated to analysing the spread of odours [17]. An unquestionable advantage of the system in relation to the methodology defined in the Regulation of the Minister of Environment of 26 January 2010 on reference values for certain substances present in the air (Journal of Laws 2010 No. 16, item 87) [18] is the possibility of taking spatially variable terrain parameters (relief and use) and changes in meteorological conditions over time into account. This is particularly important for the spread of odours which, in most cases, are incidentally bothersome [19]. To identify the odour impact zones around landfills, interactive software (for modelling and mapping) was used to estimate the rate of odour emission and the atmospheric dispersion of odorous compounds in relation to atmospheric stability, as well as to map the impact zones to delineate the impacted areas and estimate the affected population within the impact zones. This combination of methods for detecting odorous compounds enabled us to obtain a reliable result that will provide an appropriate level of confidence in the conclusions.

The first component of the system is the Weather Research and Forecasting Model (WRF), which provides the necessary input meteorological data for further calculations. The WRF model is a mesoscale numerical dynamic model with data assimilation that is designed to simulate and predict atmospheric circulation [20]. The information from the publicly available NCEP/NCAR Reanalysis project is used as input data in the meteorological model, which takes into account all measurement information from ground, aerological, and precipitation measurement networks as well as data from surveys and satellite observations on a global scale. Based on this information, a simulation of annual weather conditions for the area of Poland was performed in a 5 km resolution grid. Output data from the WRF model calculations are input data for the CALMET meteorological preprocessor, which allows spatial concentration of the meteorological information and also determines the data fields and meteorological parameters necessary for calculations of dispersion. The range of the meteorological grid defined in the CALMET preprocessor (Scheme 1) must include all sources analysed in the area. In order to better describe the terrain characteristics, the calculations at this stage also use more detailed data on land use and relief [11]. Dispersion of odours is strongly conditioned by local atmospheric dynamics. The assessment of odour impacts needs to take into account the variability of local atmospheric dynamics [21].



Scheme 1. Scheme of the modelling system (authors' own elaboration).

The most important element of the system is the CALPUFF puff dispersion model. This is an advanced second-generation Gaussian cloud model, which is currently one of the best models of puff dispersion available on the market; it is primarily used for assessment of the impacts of technological and/or energy sources. The model was developed by Sigma Research Corporation (SRC), part of Earth Tech. Inc. (California, USA) [22,23]. The advanced descriptions of physical processes that occur in the atmosphere (e.g., taking into account the effects of mixing layer thickness, precipitation, no-wind periods, etc.) make it highly sensitive to the spatial characteristics of the environment and the variability of the meteorological field. It also has built-in modules that allow one to take into account, among other things, dry and wet deposition and simple chemical transformations.

An indispensable element of the system is the provision of appropriate emission data [24]. Unlike the Polish reference methodology, the CALPUFF dispersion model can simulate the spread of pollutants from various types of sources [25]. The model allows the inclusion of point emissions with set technical parameters, surface emissions (polygons), volumetric emissions (specific sources where the emissions are described as a certain volume of the pollutant), and linear emissions, while keeping their characteristics in the calculation. For all types of sources, the user can input coefficients of emission time variability (e.g., daily, hourly, monthly). In the model, calculations can be performed separately for each source (or a type or group of sources), and then the individual output files can be summed [26]. The CALPUFF model is used to determine the concentrations of selected compounds in the form of hourly series stored in a regular grid of the calculation field or discrete user-defined receptors. The receptors can cover a wide area, but the area cannot be larger than the meteorological information prepared using the CALMET preprocessor. These series are saved into output files and can be repeatedly processed using an appropriate postprocessor to determine the selected statistics (in accordance with the relevant regulations of the Minister of Environment), which are then visualized using Geographic Information System (GIS) programs. The use of the CALMET/CALPUFF model is particularly important from the point of view of odour impact assessment because greater nuisances are caused by instantaneous changes in odour intensity [27]. This specificity can only be taken into account in a model that uses time-varying meteorological data (with at least hourly time resolution). A detailed description of terrain parameters is also critical, as these parameters affect the shape of the pollutant plume.

The calculations also take into account the effect of an emitter that is part of an installation for the composition of alternative fuels as a source of particulate matter emissions. The calculations were based on meteorological data from 2018, and it was assumed that both favourable and unfavourable meteorological conditions affecting the spread of pollutants occurred in the base year. The most important meteorological elements determining the variability and spread of pollutants in the atmosphere are wind speed and direction, temperature, precipitation, relative humidity, and atmosphere balance class. The applied reference methodology based on the simplified perennial mean of the wind rose does not sufficiently simulate the abovementioned parameters, as it does not allow for short-term analyses of odour or pollution concentrations. In addition, there have been significant changes in climate over the last decade, and the conditions today are significantly different from the averages used in analyses based on the reference methodology. This applies especially to thermal and rainfall conditions, but changes in atmospheric circulation have also been observed. An analysis of the information contained in the Polish climate monitoring bulletins issued by the Institute of Meteorology and Water Management since 2010 justifies the use of current meteorological data in air quality analyses. Therefore, the meteorological conditions from 2018 were selected to represent the conditions of the last decade for the purpose of the analysis of the impact of the landfill on air quality.

The CALMET/CALPUFF model was selected due to its ability to take the spatial variability of the relief and land use, as well as the temporal and spatial variability of the meteorological conditions, into account. These parameters significantly influence the spatial distribution of pollutant concentrations (especially odours). Experience shows that long-term (annual) averages are much less sensitive to all adverse factors, such as wind direction and low height of inversion. As a result, the relevant criteria for short-term averages are exceeded much faster than for annual averages.

2.2. Case Study: Analysis of the Odour Impact of the Landfill Cell

The analysed facility, i.e., the waste management plant, is located in southwestern Poland, where a landfill site for non-hazardous and inert waste is situated. The plant covers an area of about 16 ha. Its activities include:

- Receiving and controlling the volume and quality of waste;
- Waste disposal via storage in landfill cells, compaction, and covering with an insulation layer of waste;
- Use of selected types of waste to build slopes, including embankments;
- Shaping the crest of the landfill site to create the current reclamation (biological) cover and to build temporary access roads to the landfill cells.

2.3. Field Conditions

An important element that affects the distribution of pollution concentrations is the use of land and topographical relief. The relief mainly modifies the shape of the pollutant plume, while the use also affects the deposition of pollutants [28]. This is particularly important from the point of view of the odour effect. The following figures present the information about the terrain used in the model (Figure 1).

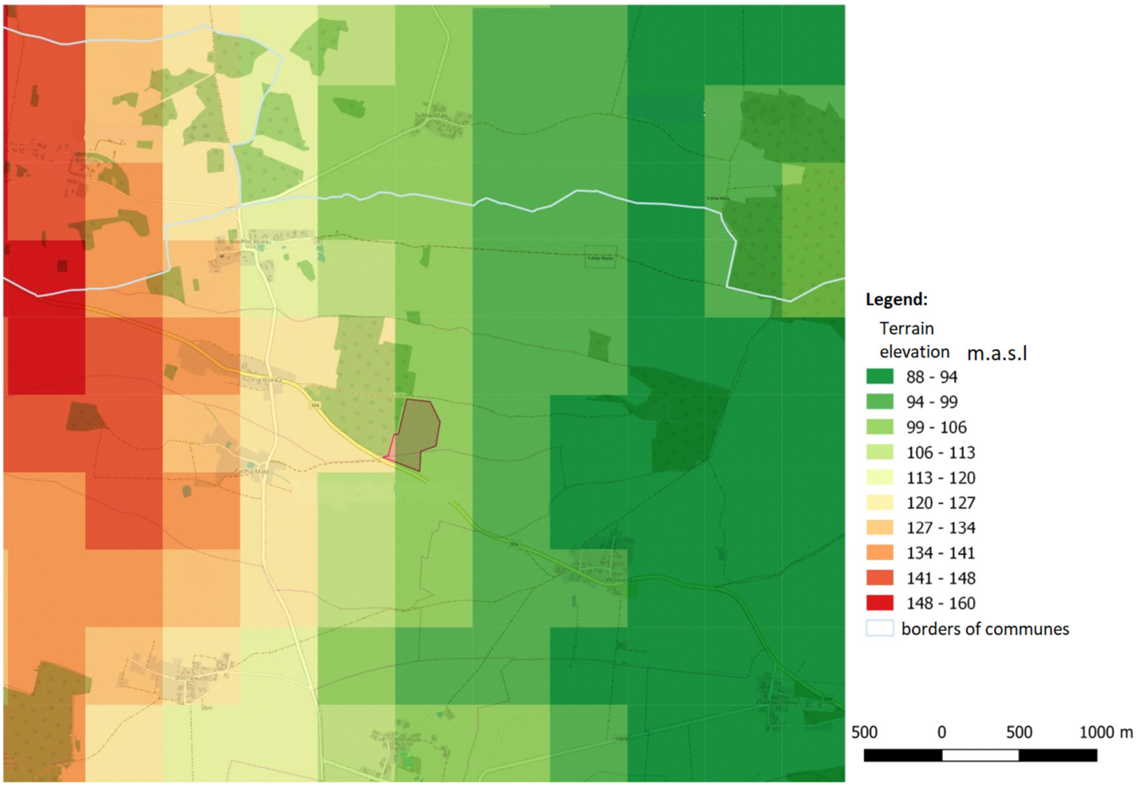


Figure 1. Topographical relief included in the model.

The topography of the area is quite diverse. Over an area of about 25 km, there is an altitude difference of 72 m, with the terrain rising to the west. The area of the landfill is located 99–106 m above sea level. The closest surroundings of the facility include forests (to the west) and agricultural areas, which have the highest percentage in the area studied. A large forest complex is located to the east. The buildings in the area are dispersed.

2.4. Meteorological Conditions in the Base Year of Calculations

The most important meteorological elements that determine the transformations and spread of pollutants in the atmosphere include wind speed and direction, temperature, precipitation, relative humidity, and atmospheric stability class [29]. These especially concern the thermal or precipitation relations, but there are also changes in atmospheric circulation. The analysis of information contained in the climate monitoring bulletins issued in Poland since 2010 by the Institute of Meteorology and Water Management justifies the use of current meteorological data in air quality analyses. Therefore, for the analysis of the impact of the landfill on air quality, the meteorological conditions present in 2018 were chosen to represent the conditions of the last decade. Below is an analysis of the basic meteorological elements and phenomena from the selected base year for the area corresponding to the location of the landfill site.

2.5. Wind Speed and Direction

The spread of odours and pollutants is mainly affected by wind conditions, especially wind speed and direction. No-wind periods and low wind speeds deteriorate horizontal air ventilation, which, in turn, contributes to increased concentrations of pollutants and odours. Wind speed affects the speed of transport of air with pollutants, while its direction determines the route of their transport. In relation to the modelling results, wind speed is analysed by determining its mean value per hour (at 10 m height). It should also be noted that the wind field can be modified to a large extent by local conditions, such as the presence of obstacles. Therefore, with such a small and relatively complex area of analysis, the use of a denser grid of field parameters is extremely important. The mean annual wind speed near the landfill site, which was determined using the model data for the base year of the analysis, was about 4 m/s. The wind speed was categorized into specific ranges based on the frequency of occurrence of winds (Figure 2). The analysis shows that winds with speeds from 3.1 to 5.1 m/s (47.8% of all cases), which are described as mild, were the most frequent. Weak winds (1.5–3 m/s) in the area occurred for ca. 25.3% of the year. Moderate winds of 5–8 m/s were slightly less frequent (18.1%). Strong winds of more than 10 m/s occurred in about 0.2% of the year. The phenomenon of no-wind periods, i.e., the occurrence of wind speeds below 1.5 m/s, occurred at a frequency of 6.2% of the year.

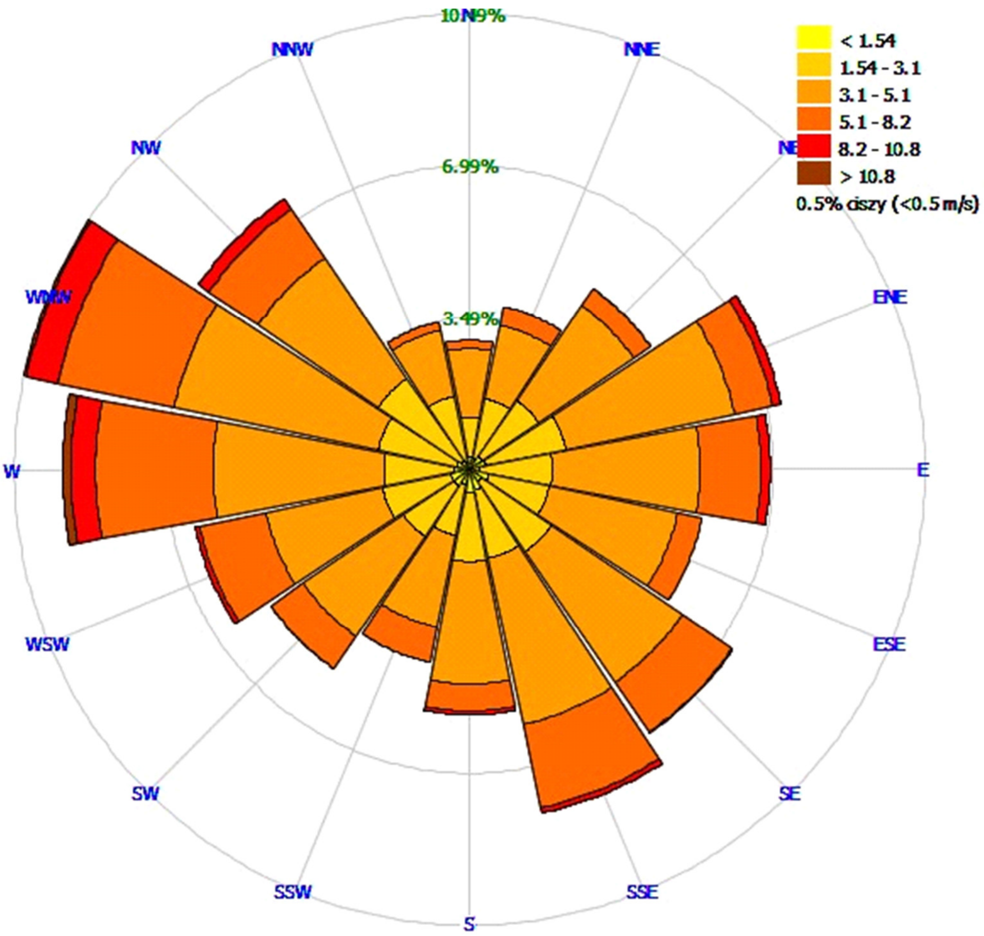


Figure 2. Distribution of wind directions and speeds in the base year for the mesh of the meteorological grid corresponding to the location of the landfill site.

The simplest form of presentation of the wind distribution in the selected period is with a wind rose determined for the area around the landfill site based on a time series of one-hour wind speeds. Annually, the prevailing winds in this area were those from western sectors (W), which is consistent with the wind rose presented in the Polish climate monitoring bulletin. In the summer months, lower wind speeds prevailed, and the most frequent direction of wind flow was north-western (NW). In winter, winds with higher speeds occurring mainly from the west were more frequent. There was also a significant percentage of winds from the south-eastern sector (SS).

2.6. Air Temperature

The mean air temperature determined from the WRF/CALMET models for the studied year was 10.1 °C. According to the time distribution of the mean air temperature, the coldest month was February (−3.1 °C), and it was the only month of the year with an average negative temperature. The warmest month was August, with a monthly average exceeding 21 °C. According to the climatic classification, the base year was extremely warm, as was the five-year period preceding that year, which additionally indicates the validity of choosing a methodology other than the reference methodology.

2.7. Atmospheric Stability Classes

A very important parameter for the spread of pollutants is the Pasquill atmospheric stability class, which describes vertical air movements with respect to the temperature gradient and wind speed in order to determine the movement of polluted air in a pollutant plume.

Depending on the temperature difference between rising and ambient air, there are three basic states of equilibrium in the atmosphere: unstable, neutral, and constant. Intermediate states are also defined between them. The following division into six classes of atmospheric stability is generally accepted:

- Class 1—very unstable conditions;
- Class 2—unstable conditions;
- Class 3—slightly unstable conditions;
- Class 4—neutral conditions;
- Class 5—slightly stable conditions;
- Class 6—stable conditions.

Classes 1 and 2 are unfavourable for the spread of pollutants, as the exhaust gas plume rises and falls due to intensive air movement. Classes 5 and 6, which are characterized by inversion conditions, are very unfavourable, with the pollutants remaining in the area at low altitudes because the conditions do not allow them to disperse.

In 2018, atmospheric stability class 4 (43.5% of the time), representing neutral conditions for the spread of pollutants, was by far the most common. Class 1, described as very unstable, was very rare. In total, the percentage of very unfavourable classes for the spread of pollutants was 42.5% in 2017. This distribution undoubtedly helps reflect the unfavourable conditions that affect the formation of episodes of high concentrations of pollutants. It can be assumed that the analysis took the worst possible impacts of the analysed facility into account.

2.8. Precipitation

Depending on its intensity, type (rain, snow), and duration, precipitation can lead to different degrees of washing out air pollutants from the atmosphere. The precipitation over the year was characterised by the occurrence of the highest levels in June (almost 117 mm) and July (93 mm). The lowest precipitation was observed in February (6 mm) and November (16 mm). The total annual precipitation in 2018 was 523 mm, and, therefore, the year can be considered as very dry and unfavourable for washing out pollutants from the atmosphere.

2.9. Relative Air Humidity

The relative humidity parameter is an important factor in the spread of odours. The course of average monthly relative humidity values indicated that significantly lower values of relative humidity occurred in the summer, and the highest occurred in the winter and autumn months.

2.10. Emission Data

The information contained in the report on the evaluation of odour concentration in the air was used to determine the pollutant emissions. Based on the analysis, emitters were selected to calculate odour and pollution concentrations. The impact of the landfill site on air quality was then analysed. The impact of the odour emission source was identified based on the report on the olfactometric measurements. The emission source had an unstructured surface character, and the related emissions occurred at different periods and with different intensities. The landfill cell was not equipped with a degassing system, and, therefore, more odour emissions could be expected from the entire area, which was not subjected to reclamation. The area could change over the course of a year. Emissions from the site occurred constantly and were mainly dependent on the microbiological processes in the landfill cells, which, in turn, were related to the types of materials stored.

The results of olfactometric measurements and selected meteorological parameters made at five measurement points near the landfill site (report from accredited research) were used to determine the emission factor used in the final modelling of odour concentrations (Figure 3).

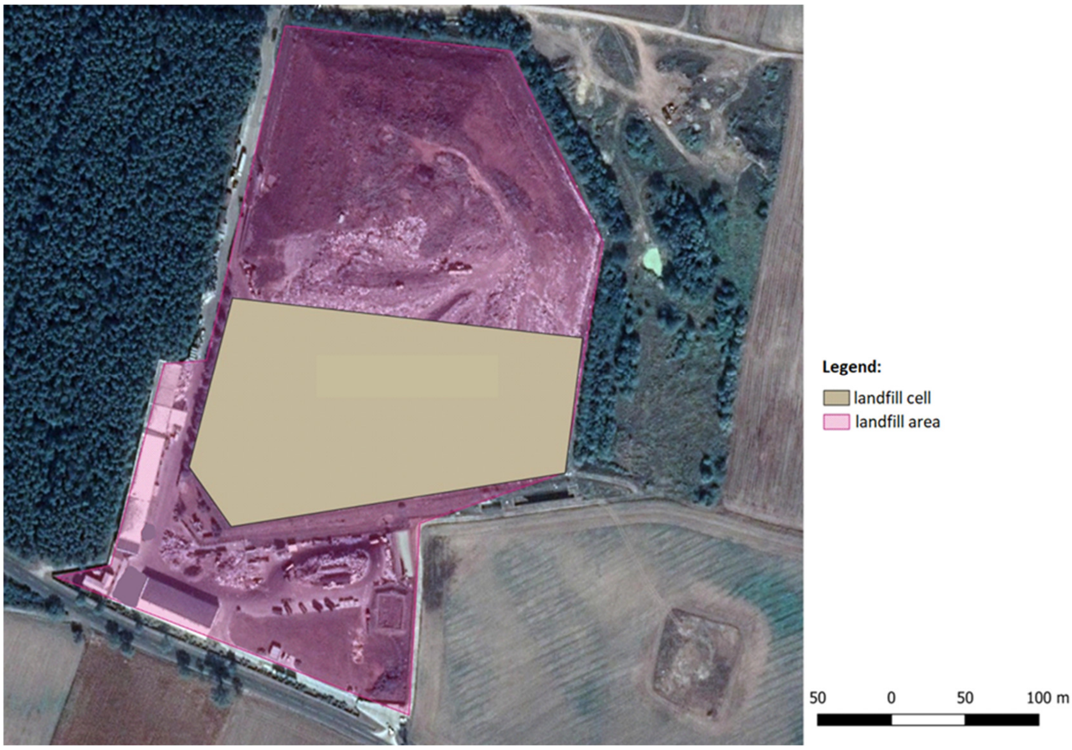


Figure 3. Layout of the emitters on the landfill site.

The odour emission factors for the source were estimated based on statistical analyses using the trial and error method (Table 1).

Table 1. Odour emission factor for the sources of the landfill site.

Source	Index Value [ou/m^2/s]
Cell no. 3 for waste storage	5.1

The above factor is the basis for the determination of the olfactory impact of the facility. The basic threshold used as a reference for the assessment of the odour nuisance of the facility is an odour concentration of 1 ou/m^3. This value may be exceeded during the year for a certain period of time. The three threshold values for the frequency with which the above values are exceeded in relation to the annual series of concentrations are 15, 8, and 3% of the hours in a year. The system allows a transitional period for the implementation of the law; during this period, the higher levels of 15 and 8% would apply and would then be tightened to 8 and 3%, respectively.

3. Results

3.1. Parameterization of the Dispersion Model

Calculations of contamination concentrations with the CALMET/CALPUFF model were carried out for the base year 2018. A set of discrete receptors based on a 100 m grid was used for the calculations, covering an area with a radius of 2.5 km from the landfill site (Figure 4).

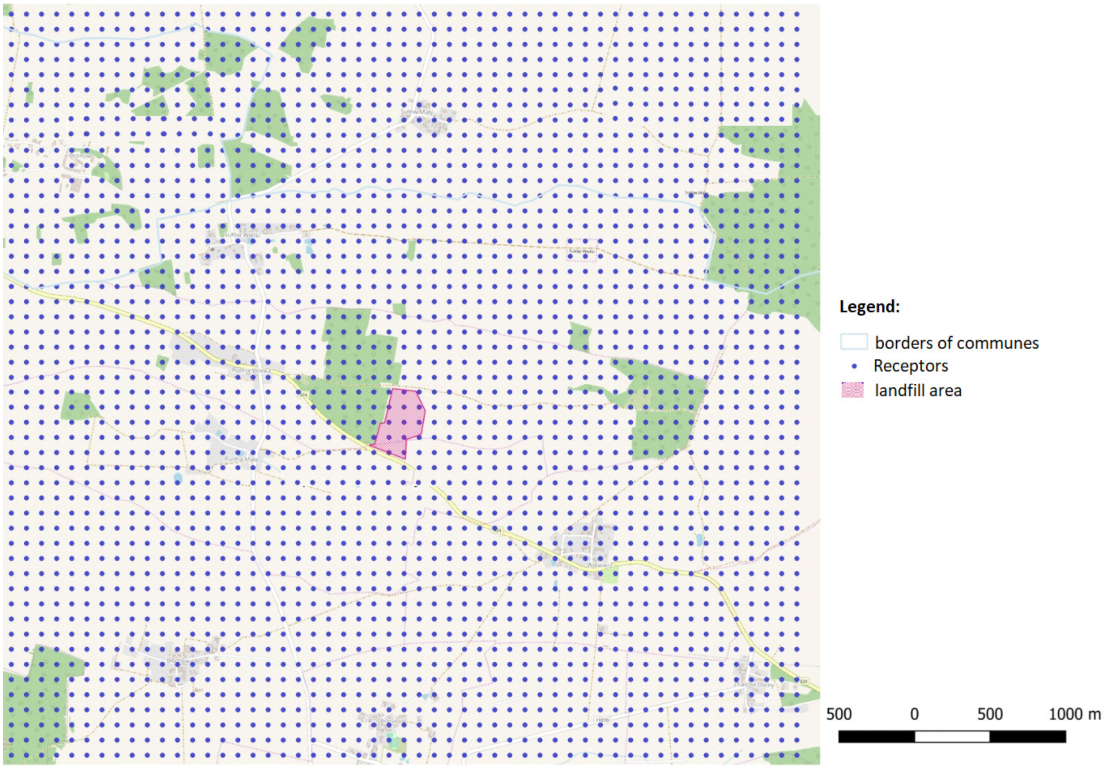


Figure 4. Layout of receptors.

The model's calculations of odour concentrations were carried out in separate patterns for individual emitters, and the concentrations in the receptors and hours were then summed to obtain the total impact of the facility. The pollutant concentrations were recorded as sequences of one-hour values of concentrations of dust pollutants and odours in the receptors, which were stored in binary output files of the model. Next, they were statistically processed to determine specific characteristics.

3.2. Odour Nuisance Analysis of the Facility

The analysis of the odour impact of the facility took three basic statistical parameters into account: the number of hours in which the odour detection threshold (1 ou/m^3) is exceeded and the mean one-hour odour concentrations for 3 and 8% of the hours in a year. The results are presented below. The figures show the range of the isoline of the odour detection threshold and odour recognition threshold (Figure 5).

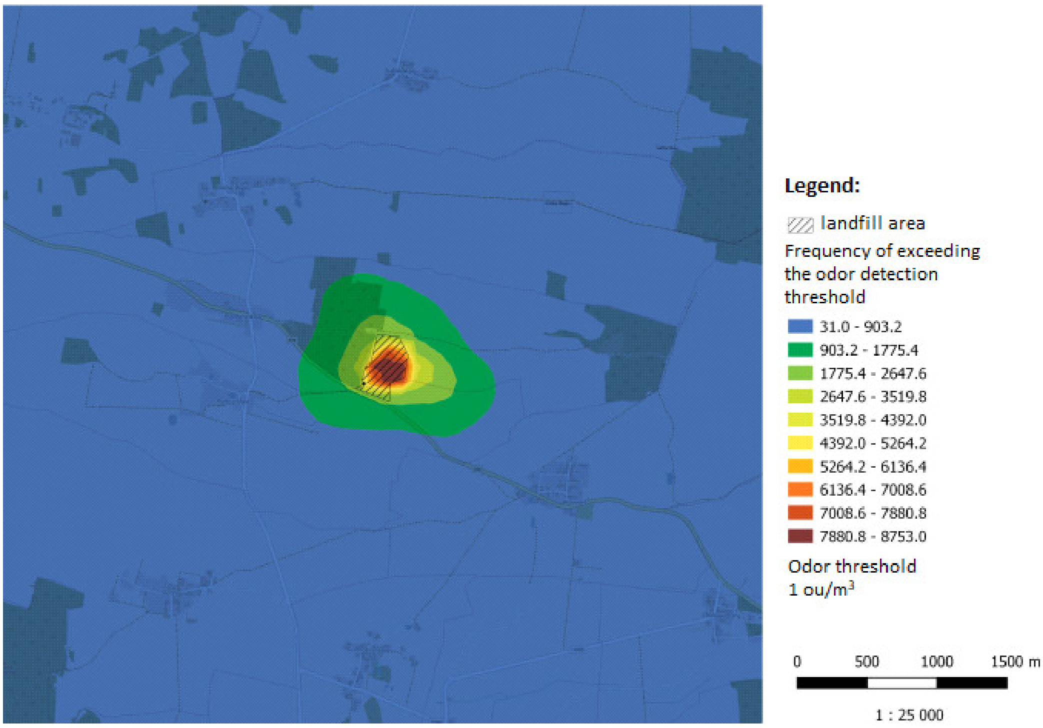


Figure 5. Number of hours in which the odour exceeds the detection threshold.

The analysis of the results of mathematical modelling indicates the significant odour impact of the landfill (Figure 6). In the area of the landfill cell, exceeding the odour detection threshold, can be expected almost all year round. Single hours where the odour threshold is exceeded (minimum 31 h) can occur in nearly the entire analysed area. The pollution plume usually moves east and northwest.

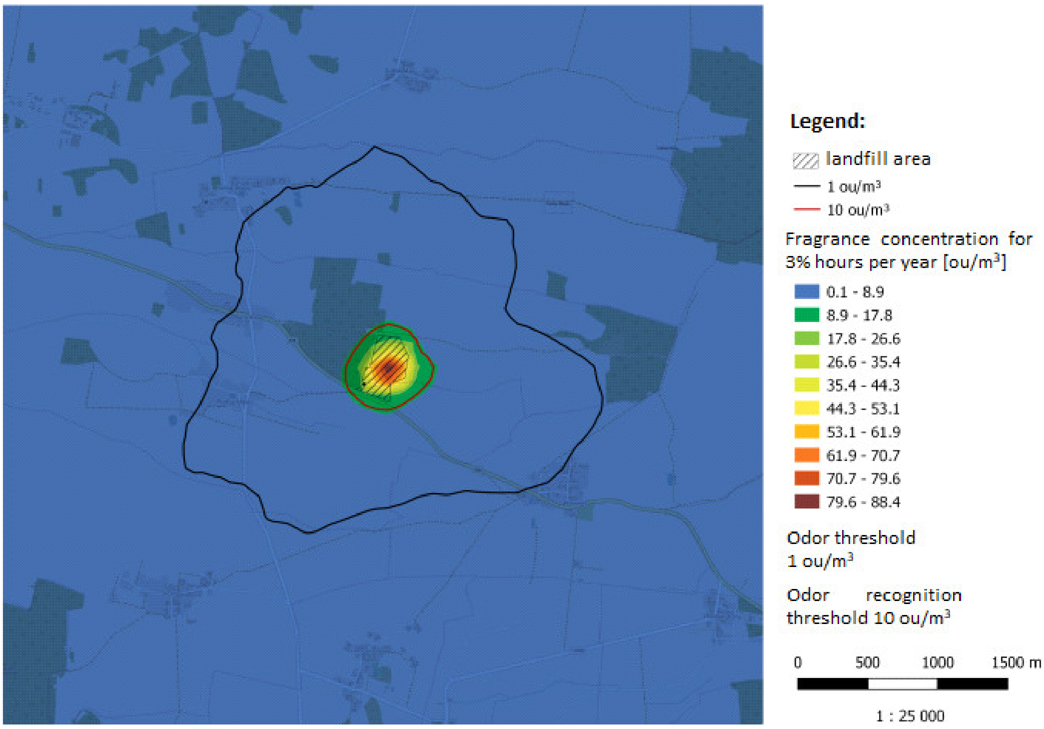


Figure 6. Odour concentrations: mean levels for 3% of the hours in a year.

The odour concentration levels for 3% of the hours in a year indicate that the odour detection threshold is exceeded in an area of ca. 1.5 km around the source. The maximum odour concentration for 3% of the hours in a year was about 88 ou/m^3. Concentrations above the odour recognition threshold occur in the immediate vicinity of the source (Figure 7).

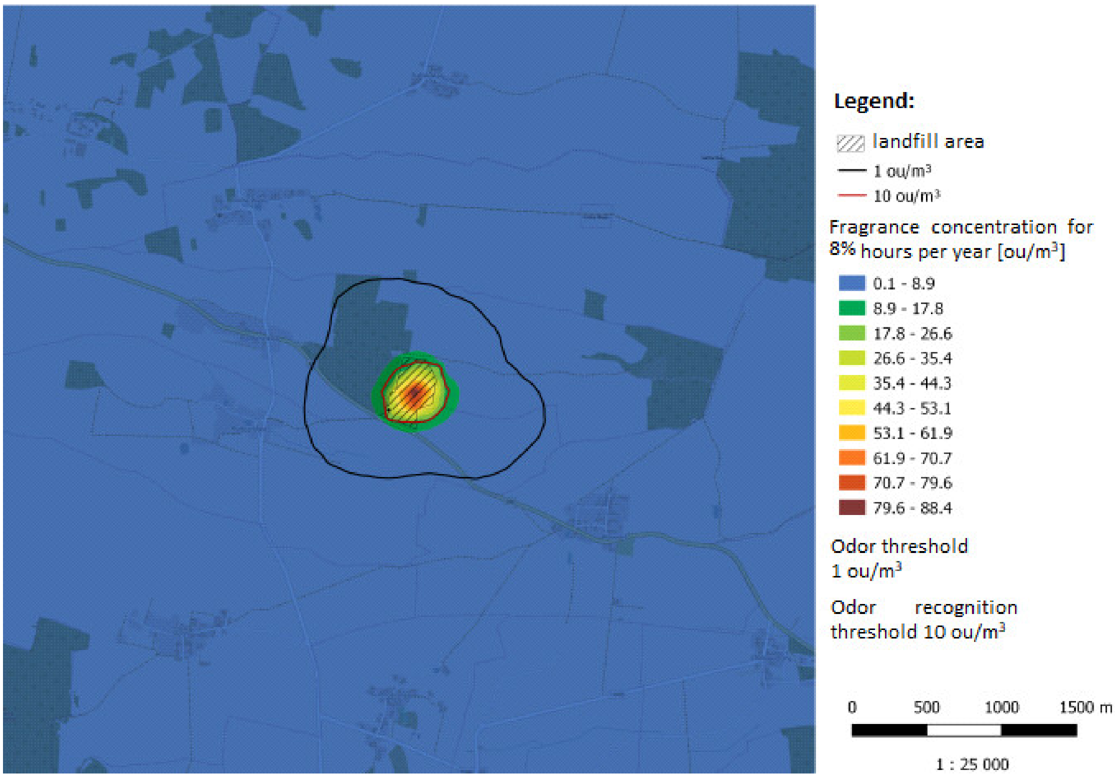


Figure 7. Odour concentrations: mean levels for 8% of the hours in a year.

The odour concentration levels for 8% of the hours in a year indicate that the odour detection threshold is exceeded in an area of ca. 1 km around the source. The maximum odour concentration for 8% of the hours in a year was about 62 ou/m^3. Concentrations above the odour recognition threshold occur in the immediate vicinity of the source and are almost restricted to the area of the plant.

4. Discussion and Conclusions

Regarding the issue addressed in this study, it is important to clarify and define relevant influencing elements at the stage of planning and operation due to the potential effect on environmental, property, and community values. Moreover, the subject matter may be a predictor of solutions related to the determination of health risk. The modelling results, which were obtained on the basis of environmental research, show the possible levels of impact of this type of technological facility on the environment in terms of the influence of odour compounds. The described estimation methodology can help validate potential solutions that may eventually lead to a reduction in the potential impact associated with the operation of landfills.

The analysis of the odour impact of the plant clearly indicates its significant impact on the air quality in the studied area. The range of the plant's impact may even reach up to 1.5 km, and in the nearest locality, it might exceed the odour perceptibility threshold for more than 3% of the hours each year. Some researchers have indicated that odour nuisances are locally concentrated in zones that are 200 to 300 m beyond the boundaries of an area [5]. However, taking into account the fact that the landfill is located within an agricultural area, the incidental odour impact in this area may also be associated with periods of intensive fertilization and a roadside ditch that collects municipal sewage from roadside households. The results of the olfactometric analysis and odour dispersion simulation show that the odour impact might be relevant for a specific downwind area that is near the landfill, and that the most problematic odour source is a lagoon where the leachate is stored uncovered [6]. It should be borne in mind that the obtained emission factor was verified by the measurement. In order to determine emission factors in landfill facilities more precisely in the future, it is advisable to carry out more measurements on an annual monitoring scale. In terms of the air quality in the vicinity of a landfill site, the odour impact of a landfill cell was identified. This impact will certainly be significantly reduced when the recommended degassing system is installed in the landfill cell, which will limit its impact as an emitter to only the area where waste storage will take place. Based on the case study presented here, this research seems justified and even necessary for controlling technological processes related to the operation of landfills and, importantly, in terms of striving to reduce the odour impact of such municipal waste facilities on the environment.

The estimation of the abovementioned issues can lead to the selection of optimal operational decisions at the design and operation stages of landfills. Fine-tuning of decision-making processes in terms of these research issues and their solutions can enable local and global reduction in odour nuisances caused by technological facilities and can clarify a process of sustainable usage of natural resources that also takes local communities into account. By balancing the optimal achievable levels of impact and taking the paradigm of sustainable development into account, value can be added in the form of social approval and acceptance of such projects.

Author Contributions: Conceptualization, Ł.S. (55%), J.Z. (25%), A.C.-E. (10%), and M.A.J. (10%); data curation, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); formal analysis, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); funding acquisition, M.M. (70%) and A.C.-E. (30%); investigation, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); methodology, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); project administration, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); resources, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); software, Ł.S. (60%), J.Z. (24%), A.C.-E. (8%), and M.A.J. (8%); supervision, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); validation, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); visualization, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); writing—original draft, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%); writing—review and editing, Ł.S. (39%), J.Z. (13%), M.M. (8%), A.C.-E. (8%), M.A.J. (8%), S.D. (8%), L'.K. (8%), and P.D. (8%). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This paper presents the results of the research project KEGA 026EU-4/2018—Educational and communication support for European development strategies by profiling graduates in the field of Economics and Business Management.

Conflicts of Interest: The authors declare no conflict of interest.

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